PB92-180231

Methods of Assessing Responses of Trees, Stands and Ecosystems to Air Pollution (Chapter 7)

(U.S.) Corvallis Environmental Research Lab., OR

1992

U.S. Department of Commerce
National Technical Information Service

ERL-COR- 1445D

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before complet

1. REPORT NO. EPA/600/A-92/104	2.	3. PB92-180231
4. TITLE AND SUBTITLE Methods of Assessing Responses of Trees, Stands, and Ecosystems to Air Pollution		5. REPORT DATE 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) K. Stolte, D. Duriscoe, E. Cook, and S. Cline		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS USFS, Raleigh, NC; Nat'l Park Service, Three Rivers, CA; Lamont-Doherty Geol. Obs., Palisades, NY; METI, ERL-Corvallis, OR		10. PROGRAM ELEMENT NO. 11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS US Environmental Protection Agency Environmental Research Laboratory 200 SW 35th Street Corvallis, OR 97333		13. TYPE OF REPORT AND PERIOD COVERED Book Chapter 14. SPONSORING AGENCY CODE EPA/600/02

15. SUPPLEMENTARY NOTES
1992. Chapter 7 IN: Air Pollution and Western Forests. D. Binkley, R. Olson, and M. Böhm (eds).

16. ABSTRACT

This chapter focuses on three main types of assessments of pollution effects used in the case studies chronicled in Chapter 8 through 12 (Regional Studies of conifer forests in the west). These are measures of crown condition of individual trees; impacts on populations and communities; and temporal patterns in radial growth. The concepts behind the development of each approach are introduced with references to previous work, leading to a discussion of the state of science. The importance of quality assurance techniques to the success of any assessment of air pollution effects is also discussed.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
crown condition assessments, gaseous pollutant injury, dendrochronology		

18. DISTRIBUTION STATEMENT Release to Public	19. SECURITY CLASS (This Report) Unclassified 20. SECURITY CLASS (This page) Unclassified	21. NO. OF PAGES 66 22. PRICE

EPA Form 2220-1 (9-73)

INSTRUCTIONS

1. **REPORT NUMBER**
Insert the EPA report number as it appears on the cover of the publication.

2. **LEAVE BLANK**

3. **RECIPIENTS ACCESSION NUMBER**
Reserved for use by each report recipient.

4. **TITLE AND SUBTITLE**
Title should indicate clearly and briefly the subject coverage of the report, and be displayed prominently. Set subtitle, if used, in smaller type or otherwise subordinate it to main title. When a report is prepared in more than one volume, repeat the primary title, add volume number and include subtitle for the specific title.

5. **REPORT DATE**
Each report shall carry a date indicating at least month and year. Indicate the basis on which it was selected *(e.g., date of issue, date of approval, date of preparation, etc.)*.

6. **PERFORMING ORGANIZATION CODE**
Leave blank.

7. **AUTHOR(S)**
Give name(s) in conventional order *(John R. Doe, J. Robert Doe, etc.)*. List author's affiliation if it differs from the performing organization.

8. **PERFORMING ORGANIZATION REPORT NUMBER**
Insert if performing organization wishes to assign this number.

9. **PERFORMING ORGANIZATION NAME AND ADDRESS**
Give name, street, city, state, and ZIP code. List no more than two levels of an organizational hierarchy.

10. **PROGRAM ELEMENT NUMBER**
Use the program element number under which the report was prepared. Subordinate numbers may be included in parentheses.

11. **CONTRACT/GRANT NUMBER**
Insert contract or grant number under which report was prepared.

12. **SPONSORING AGENCY NAME AND ADDRESS**
Include ZIP code.

13. **TYPE OF REPORT AND PERIOD COVERED**
Indicate interim final, etc., and if applicable, dates covered.

14. **SPONSORING AGENCY CODE**
Leave blank.

15. **SUPPLEMENTARY NOTES**
Enter information not included elsewhere but useful, such as: Prepared in cooperation with, Translation of, Presented at conference of, To be published in, Supersedes, Supplements, etc.

16. **ABSTRACT**
Include a brief *(200 words or less)* factual summary of the most significant information contained in the report. If the report contains a significant bibliography or literature survey, mention it here.

17. **KEY WORDS AND DOCUMENT ANALYSIS**
(a) DESCRIPTORS - Select from the Thesaurus of Engineering and Scientific Terms the proper authorized terms that identify the major concept of the research and are sufficiently specific and precise to be used as index entries for cataloging.

(b) IDENTIFIERS AND OPEN-ENDED TERMS - Use identifiers for project names, code names, equipment designators, etc. Use open-ended terms written in descriptor form for those subjects for which no descriptor exists.

(c) COSATI FIELD GROUP - Field and group assignments are to be taken from the 1965 COSATI Subject Category List. Since the majority of documents are multidisciplinary in nature, the Primary Field/Group assignment(s) will be specific discipline, area of human endeavor, or type of physical object. The application(s) will be cross-referenced with secondary Field/Group assignments that will follow the primary posting(s).

18. **DISTRIBUTION STATEMENT**
Denote releasability to the public or limitation for reasons other than security for example "Release Unlimited." Cite any availability to the public, with address and price.

19. & 20. **SECURITY CLASSIFICATION**
DO NOT submit classified reports to the National Technical Information service.

21. **NUMBER OF PAGES**
Insert the total number of pages, including this one and unnumbered pages, but exclude distribution list, if any.

22. **PRICE**
Insert the price set by the National Technical Information Service or the Government Printing Office, if known.

PB92-180231

EPA/600/A-92/104

CHAPTER

7

Methods of Assessing Responses of Trees, Stands and Ecosystems to Air Pollution

K.W. Stolte, D.M. Duriscoe, E.R. Cook, S.P. Cline

Introduction

The responses of forests to air pollution in the western United States range from cellular injury on individuals to alteration of forest communities. These responses have been observed in both field studies and controlled exposure studies. A variety of methods have been developed by the USDA Forest Service, the Department of Interior's National Park Service, the US Environmental Protection Agency, academic institutions, and private consultants to determine the nature, incidence, and severity of pollution effects on Western forests.

The choice of indicators to be measured depends on the objectives of the study and the pollutants of interest (Miller 1989). Some pollutants leave elemental signatures, such as increased concentrations or presence of novel chemicals. Fluoride (Carlson and Dewey 1972) and sulfur dioxide (Nriagu 1978, Smith 1990) leave elemental signatures as well as producing distinct visible injury symptoms. Acid rain and toxic metals (e.g., zinc, vanadium, arsenic) can leave elemental signatures and can produce visible symptoms on foliage at high concentrations, with subsequent effects on vigor, growth, and productivity (Lepp 1981a, b, Wellburn 1989, MacKenzie and El-Ashry 1989). Naturally occurring stable isotopes of elements are sometimes greatly enriched or depleted in anthropogenic air masses compared to natural background levels; differences in isotope ratios may serve as markers of anthropogenic deposition, uptake by biological systems, and alteration of nutrient cycles (Krouse 1974, Jackson and Gough 1989).

REPRODUCED BY
U.S. DEPARTMENT OF COMMERCE
NATIONAL TECHNICAL INFORMATION SERVICE
SPRINGFIELD, VA. 22161

Ozone and some other gaseous oxidants (e.g., hydrogen peroxide) leave no discernible residue or elemental signature, and the only signature to be detected is the biological response of the plant. The responses of conifers in the western United States to oxidants include:

- Altered physiological processes (e.g., photosynthesis, respiration, water and nutrient cycles) (Coyne and Bingham 1982, Patterson and Rundel 1989, Grulke et al. 1989)
- Cellular injury (Evans and Miller 1972a, b, Carlson and Dewey 1972) and change in metabolites (Tingey et al. 1976)
- Macroscopic (visible) injury (Miller et al. 1963, Richards et al. 1968)
- Altered phenological cycles (e.g., increased abscission rates, altered needle initiation) (Miller and Van Doren 1982, Duriscoe and Stolte 1989, Ewell et al. 1989)
- Altered growth (increased or decreased) (Peterson et al. 1987, Miller et al. 1989; see chapters 11 and 12)
- Community perturbations (e.g., change in species diversity, importance, and cover) (Miller et al. 1982)

This chapter focuses on the three main types of assessments of pollution effects used in the case studies chronicled in Chapters 8 through 12: measures of (1) crown condition of individual trees; (2) impacts on populations and communities; and (3) temporal patterns in radial growth. The concepts behind the development of each approach are introduced with references to previous work, leading to a discussion of the state of the science. The importance of quality assurance techniques to the success of any assessment of air pollution effects is also discussed.

Crown Condition Assessments

Crown injury symptoms are the most common kind of visible pollutant injury recorded in laboratory and field air pollution studies in the West. Crown injury symptoms are measured by assessments of the stem and foliage portions of the trees. Gaseous pollutants pass through the stomata of conifer foliage and cause direct damage to photosynthetic cells, sometimes producing a diagnostic, visible foliar injury pattern. Impairment of essential biological processes in the needles may eventually lead to other crown responses such as premature needle abscission, reduced crown vigor, increased susceptibility to pathogens, and tree death (Miller 1977). Acidic deposition (wet and dry) and toxic metals are more likely to initially impact root systems and associated nutrient cycling processes.

Unless concentrations of acidic deposition or metals are very high, crown degeneration occurs secondarily from the alteration of nutrient and water cycles (Wellburn 1989, Smith 1990).

Crown response variables are macroscopic morphological alterations of the crown and stem features by air pollutants that are quantifiable within an acceptable degree of precision. Crown response variables that have been measured in Western pollution studies include foliar discoloration (visible injury), foliage longevity, needle length, foliage production, crown density, live crown ratio, cone production, stem growth, and toxic element accumulation. These variables can be quantified by visual observation, imaging and subsequent image processing, elemental analyses, and common forest mensuration techniques. Determining whether changes in these morphological features are caused by air pollution may require ancillary pathological and environmental evaluations (Wellburn 1989, Treshow and Anderson 1989, Smith 1990).

Description and Diagnosis of Gaseous Pollutant Injury

A description of the effects of gaseous pollutants on the foliage of conifers is essential to understanding the methods that have evolved in the western United States to identify and quantify pollution injury. Gaseous air pollutants found in the western United States initially injure foliage by entering intercellular spaces when stomata are open as part of the normal processes of exchanging atmospheric gases (Chapter 5). Cellular injury occurs as pollutants degrade cell membranes (Evans and Miller 1972a, b) and toxic substances accumulate. Chlorophyll degradation, cell desiccation, and cell death occur on the needle surface. Controlled fumigation studies (Miller et al. 1963, Treshow 1970, Gordon 1974) have established that ozone, sulfur dioxide, and hydrogen fluoride cause injury to cells in needles (histological injury) that result in visible foliar discolorations that are distinct and readily discernable. Foliar injury commonly includes chlorosis (yellowing) or necrosis (browning) of needle tissue.

Visible foliar injury is sometimes correlated with other pollution effects on tree crown condition and with alterations of population and community-level forest dynamics (Carlson and Dewey 1972, Miller 1977, Taylor 1980). Visible injury indicates physiological impairment that may result in measurable reductions in net photosynthesis, increases in respiration, and alteration of nutrient and water cycles within the foliage (see Chapter 5, also Patterson and Rundel 1989). However, visible injury is most effective in identifying the occurrence of phytotoxic levels of a pollutant; higher order effects (such as altered photosynthesis, growth, reproduction, or fitness) may or may not co-occur with visible damage. The

presence of visible injury symptoms indicates only that ambient levels of pollutants are sufficiently elevated to injure cells within needles. Conversely, a lack of visible foliar injury does not prove there is no pollution impact (Pye 1988; see Grulke et al. 1989 for an example with giant sequoia [*Sequoiadendron giganteum* Bucch.]).

Premature needle abscission correlates with ozone exposure and degree of foliar injury in many Western conifer species (Miller et al. 1983, Duriscoe and Stolte 1989). Chronic pollution stress has also been correlated with the size, numbers, and structure of needles produced (Coyne and Bingham 1982, Ewell et al. 1989). Responses among individual trees and species are highly variable and the thresholds where visible injury is severe enough to initiate higher order effects under field conditions are poorly known (Smith 1990).

Ozone

Controlled exposure studies and field studies of ozone impacts on Western conifer species have demonstrated that a distinct visible discoloration known as chlorotic mottle typically occurs on needle surfaces (Miller et al. 1963, Richards et al. 1968, Pronos et al. 1978, Duriscoe and Stolte 1989). Chlorotic mottle begins as a degradation of mesophyll cells below the epidermis (Evans and Miller 1972a, b, Rice et al. 1983) that includes amorphous staining of cellular contents, plasmolysis of cell walls, and cell necrosis. As the cell membrane degrades, cellular contents are lost and chlorophyll degrades. The degradation of chlorophyll is manifested on the needle surface as irregular, amorphous, chlorotic blotches with diffuse borders (Figure 7.1). This symptom is visually distinct from other nonpollutant foliar discolorations.

Chlorotic mottle or mottling first appears near the tips of needles (Miller et al. 1963, Richards et al. 1968) and progresses basipetally (toward the base) until 50% or more of the needle surface is affected, at which point necrosis of the needle tips is initiated and progresses basipetally. Trees with tip necrosis or necrotic band symptoms are more severely injured than trees with only chlorotic mottling (Miller et al. 1963). As both mottle and tip necrosis intensify, needle abscission occurs. In contrast, a healthy branch with four annual whorls of needles (whorls 1–4) is initially free of chlorotic mottle. The progression of chlorotic mottle injury, without the occurrence of tip necrosis, on the foliage of ponderosa pine is illustrated graphically in Figure 7.2. As ambient levels of ozone reach phytotoxic levels, a small amount of chlorotic mottle appears on the oldest (fourth) whorl, but abscission rates of needles have not been altered (Figure 7.2a). Increased exposure to ozone results in 30% or more of the surface area of whorl 4 covered with chlorotic mottle and a small amount of mottle on whorl 3 (Figure 7.2b). Continued exposure to ozone results in the devel-

Figure 7.1 Foliar discoloration symptoms commonly observed on symptomatic ponderosa and Jeffrey pines in the western United States: two left needles show chlorotic mottle symptoms (amorphous chlorotic blotches) from ozone injury that are observed on all needle surfaces; right needle illustrates winter fleck symptoms (smaller oval-shaped tan lesions with distinct margins) that are most frequently found on the upper surfaces of needles.

opment of mottle on needles of whorl 2 (one year old needles) and abscission of whorl 4 needles (Figure 7.2c). Still longer exposure to ozone will produce mottle on whorl 1 needles (current year's growth) and lead to the abscission of whorl 3 needles (Figure 7.2d). In the most severe cases of injury, only the current year's needles remain and have over 50% mottle (Figure 7.2e).

Chlorotic mottle has been observed on many Western conifer species and has been shown to have relatively consistent symptoms for species with long cylindrical leaves, short flat leaves, and small scalelike leaves (Richards et al. 1968, Miller et at. 1983). Chlorotic mottle appears to be the main symptom on secondary needles of ponderosa pine; tip necrosis is a more common symptom on cotyledons and primary needles. Needle length and the total number of fascicles produced may also be reduced (Miller et al. 1963, Ewell et al. 1989) when trees reach the injury stages depicted in Figures 7.2d–e (Miller et al. 1963, Miller 1977, Duriscoe and Stolte 1989).

Chlorotic mottle from ozone injury can be differentiated from foliar discoloration from pests such as fungi, scale insects, and chewing and sucking insects (Hill et al. 1970, Miller 1977, Pronos et al. 1978) based on the appearance of the symptom and the pattern of development of the symptoms. *Elytroderma deformans* (elytroderma needle cast fungus) causes a reddish-brown foliar discoloration and premature abscission of ponderosa pine needles but can be differentiated from ozone-induced chlorotic mottle by the brownish color of the needles, the presence of fruiting bodies on the needles, and the presence of witches brooms (tightly packed profusions of short branches in the crown). Similarly, *Lophodermella cerina* (pine needle cast) causes reddish-brown discoloration of ponderosa pine needles with a distinct band near the middle, and premature needle abscission which results in thin crowns (Walters 1978).

Abiotic foliar injuries such as winter fleck (Miller and Evans 1974), salt, drought, lightning and winter injury (Walters 1978) can be visually distinguished from ozone injury by the appearance of the symptom, the pattern of development on the needles, and effects on the tree crown. Drought stress on conifers causes an overall discoloration of all the needles, with the tips sometimes turning brown, and death of the crown starting at the top and working down (Walters 1978). Ozone injures the older whorls of needles first and typically causes crown death, starting at the bottom and progressing upward (Miller 1977).

Sulfur dioxide

Exposures of Western conifer species to sulfur dioxide in the field and under controlled conditions have typically shown discoloration of foliage (tip necrosis) on needle surfaces (Barrett and Benedict 1970, Treshow and Anderson 1989). Tip necrosis, usually without any dark band separating green (uninjured tissue) from brown (necrotic tissue), initially begins within the mesophyll parenchyma cells as chloroplasts become granulated (amorphous staining), followed by cell plasmolysis, collapse and necrosis. This initial pattern of injury is histologically similar to ozone injury. Mesophyll injury due to sulfur dioxide, in contrast to ozone injury, is followed by degradation of the vascular tissues. Albuminous cells of the phloem elements, and transfusion parenchyma, hypertrophy and eventually collapse (Carlson 1974). Endodermal cells eventually collapse as necrosis becomes more severe.

The tips of the needles are affected first because sulfur oxides that cannot be assimilated by the needle into amino acids are transported to the needle tips as toxic degradation products which cause cell death. Tip necrosis first appears at the tips of older needles and progresses basipetally until much of the needle surface is affected, and abscission of the needle begins. Branch mortality begins in the lower crown and progresses to the apex. The inner portions of the crown die before outer portions of the crown (Carlson 1974). Tip necrosis symptoms have been observed on many Western conifer species (Davis and Wilhour 1976) with relatively consistent expression for species with different needle shapes. Although tip necrosis appears to be the predominant symptom on primary and secondary needles of Western conifers, it cannot by itself be considered a diagnostic symptom to distinguish sulfur dioxide foliar injury from other visible foliar symptoms. Tip necrosis of conifer needles can be caused by a variety of other biotic and abiotic agents including drought, nutrient stress, and insects (Barrett and Benedict 1970).

Because sulfur dioxide injury results from the bioaccumulation of sulfur products in the needle tips, analyses of sections of the necrotic needle tips should reveal higher levels of these sulfur compounds than other sections of the same needle or unaffected needles in the same whorl. Severely damaged Douglas-fir needles (severe foliar discoloration) close to a pulp and paper mill in Montana had sulfur concentrations of 29% compared to needles with moderate foliar discolorations (22% sulfur), slight foliar discoloration (18% sulfur), and no visible foliar discoloration (3% sulfur) (Carlson 1974).

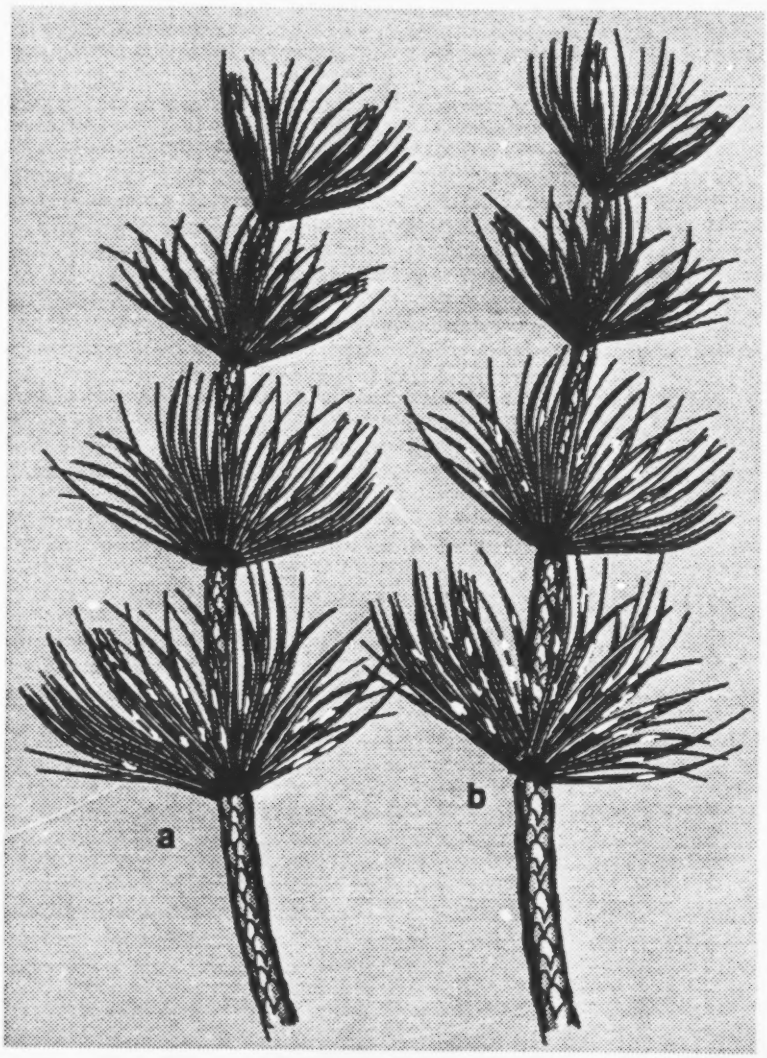


Figure 7.2 Progression of ozone-induced chlorotic mottle injury on ponderosa or Jeffrey pines. (a) Injury is first manifested on oldest whorl (4th whorl) of needles as chlorotic (yellow) blotches. (b) Chlorotic mottle injury intensifies on whorl 4 and begins to affect whorl 3.

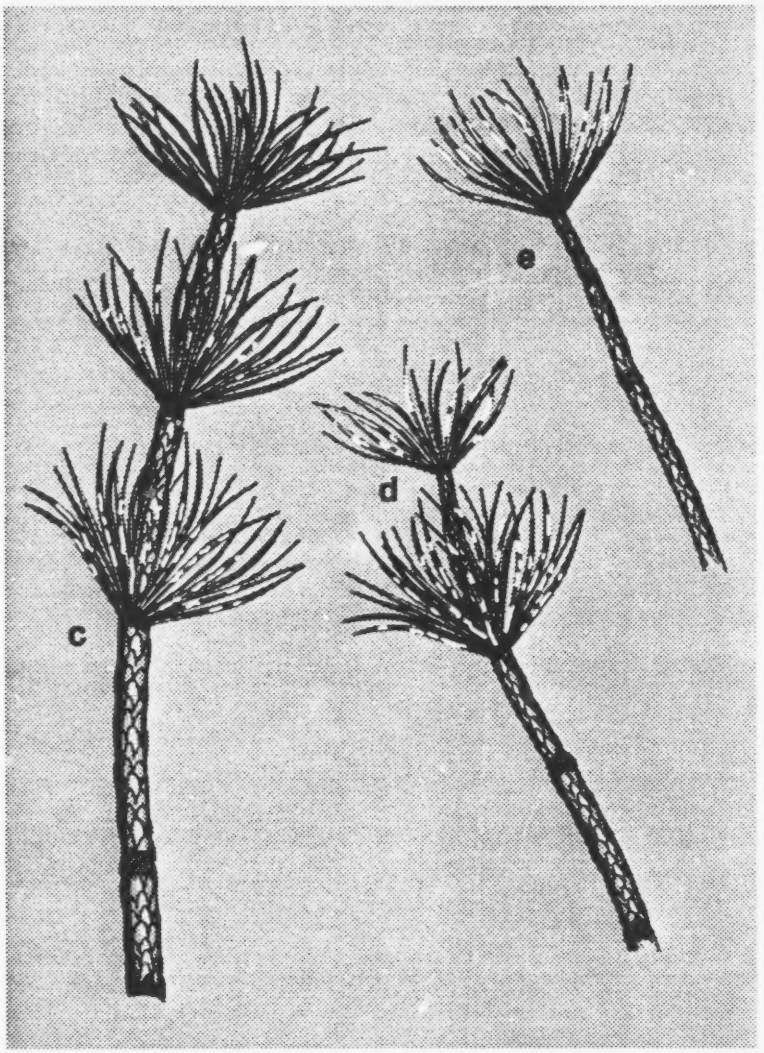


Figure 7.2 (continued) (c) Whorl 4 has abscised, injury on whorl 3 intensifies, and whorl 2 becomes injured. (d) Whorl 3 abscises as injury on whorl 2 intensifies and whorl 1 (last initiated whorl) becomes injured. (e) Severely injured branch; intense chlorotic mottle on whorl 1; all older whorls have abscised.

Hydrogen fluoride

Field and controlled exposure studies of hydrogen fluoride effects on Western conifer species have demonstrated that visible discoloration appears as tip necrosis on needle surfaces (Solberg et al. 1957, Treshow and Pack 1970, Carlson and Dewey 1972, Carlson and Hammer 1975, Davis and Wilhour 1976, Bunce 1979, 1984). Tip necrosis is commonly separated from green healthy tissue by a distinct reddish-brown band. The injury observed on needle surfaces initially begins with chloroplast granulation of mesophyll palisade parenchyma cells near the stomata. Hypertrophy of phloem, transfusion parenchyma, and albuminous cells crushes transfusion tracheids and phloem elements. Enlarged nuclei are always associated with hypertrophied cells. Resin canals are often occluded by hypertrophied epithelial nuclei and tissue (Carlson and Dewey 1972).

Needle tips are first affected because hydrogen fluorides are toxins that are transported to the needle tips and cause cell death. Tip necrosis first appears at the tips of younger needles and progresses basipetally until much of the needle surface is affected, at which point abscission of the needle begins. Tip necrosis has been observed on many Western conifer species (Treshow and Pack 1970). Tip necrosis of conifer needles similar to hydrogen fluoride injury can be caused by a variety of other biotic and abiotic agents including drought, nutrient stress, and insects. Because hydrogen fluoride injury results from the bioaccumulation of fluoride in the needle tips, analyses of necrotic needle sections should reveal elevated levels of fluoride.

Other pollutants

In the West, other air pollutants such as nitrogen oxides (NO_x), ammonia/ammonium (NH_x), peroxyacetylnitrate (PAN), chlorides (Cl_2, HCl, NaCl), acidic deposition (wet, dry, and aerosol), and ethylene (C_2H_4) have not been documented to cause extensive visible foliar discolorations on Western conifers. This is probably owing to the relatively low ambient concentrations of these pollutants in Western forests, the lack of research near point sources of these pollutants, and other intrinsic factors such as the apparent tolerance of perennial plants to PAN. When concentrations of these pollutants are high enough to cause foliar injury to coniferous or deciduous species, symptoms include (Jacobson and Hill 1970):

- Nitrogen oxides: interveinal necrotic lesions (broadleaf plants) similar to sulfur dioxide injury; tip necrosis of conifers.
- Ammonia/ammonium: interveinal and marginal chlorosis/necrosis similar to sulfur dioxide injury; tip necrosis of conifers.

- Peroxyacetylnitrate: bronzing of the lower leaf surfaces of herbs.
- Chlorides: marginal, interveinal, and tip chlorosis/necrosis (chlorine); random necrotic lesions (hydrogen chloride); tip necrosis (sodium chloride).
- Acidic deposition: random necrotic lesions.
- Ethylene: epinasty of leaves/stems; injury to flower sepals.

Ancillary Factors

The success of any assessment method depends on more than just technically correct implementation of the method. The effect of where and when the method is applied must be considered in evaluating results, and effects of confounding factors need to be considered. This section discusses some of the important ancillary considerations in conducting crown condition assessments.

Timing of injury evaluations

The timing of field injury evaluations is important in quantifying pollution injury in natural stands. Although not well documented, annual cycles of the severity of foliar discoloration and foliage retention occur, influenced by seasonal peaks of ozone dose, phenological cycles of the plant, and environmental factors. Field evaluations of the crown conditions of Jeffrey and ponderosa pines in the western United States are often conducted in the early fall when symptom severity is high (following high summer ozone concentrations) and needle retention is relatively low (due to summer drought) (Miller and Millecan 1971, Pronos et al. 1978, Vogler 1982, Duriscoe and Stolte 1989).

Selection of species

The selection of pollutant sensitive species, if the information is available, is an important method in any field study of air pollutants and conifers. The sensitivity of a species to air pollution is commonly determined by chamber fumigations or results from field studies (sites across a pollution gradient) so that target species are selected before the beginning of field injury determinations (see Chapter 5). Varieties or populations of a species can have different sensitivities to pollutants. For example, ponderosa pine (var. *scopulorum*) in the Front Range of the Rocky Mountains in Colorado is relatively tolerant to ozone (Spotts 1969, James and Staley 1980, Miller et al. 1983, Aitken et al. 1984), while the same variety growing in the mountains of southern Arizona appears to be more sensitive (Duriscoe 1987a; Chapter 10). Species that have been

documented as the most sensitive to ozone include ponderosa pine in California (*Pinus ponderosa* var. *ponderosa*), ponderosa pine from central-southern Arizona (vars. *scopulorum* and *arizonica*), Jeffrey pine (*Pinus Jeffreyi*), western white pine (*Pinus monticola*), and white fir (*Abies concolor*) (Richards et al. 1968, Miller et al. 1983). Sulfur dioxide sensitive species include: western larch (*Larix occidentalis*), ponderosa pine (vars. *ponderosa* and *scopulorum*), Douglas-fir (*Pseudotsuga menziesii*), and subalpine fir (*Abies lasiocarpa*) (Barrett and Benedict 1970, Davis and Wilhour 1976). Fluoride sensitive species include Douglas-fir, lodgepole pine (*Pinus contorta*), western larch, ponderosa pine (var. *scopulorum*), western white pine and blue spruce (*Picea pungens*) (Treshow and Pack 1970, Gordon 1974, Carlson and Hammer 1975, Davis and Wilhour 1976, Bunce 1979, 1984).

Foliage factors affecting sensitivity

Evans and Miller (1972a, b) indicated that differences in the sensitivity of conifers to ozone in California could be explained in part by the internal morphology of needles. This difference in tree sensitivity due to leaf morphology may explain why some populations of conifer species known to be sensitive to ozone appear to be more tolerant when grown in areas of extreme winter temperatures (e.g., *Pinus ponderosa* var. *scopulorum*). Changes in leaf morphology, such as increased sclerophylly as a result of low winter temperatures, may account for the relative higher tolerance of the Colorado population of *Pinus ponderosa* var. *scopulorum* to ozone (Aitken et al. 1984; Chapter 9) compared to the southern Arizona population (Duriscoe 1987a; Chapter 10). Additional work is needed to determine if the relationship between sclerophylly and increased foliar tolerance to air pollutants is due to reduced rates of gas exchange or increased tolerance within the foliage.

The phenological development of foliage alters its sensitivity to air pollutants (Coyne and Bingham 1982, Miller et al. 1982, Patterson and Rundel 1989). Newly initiated leaves are typically more tolerant of air pollutants because stomata have not become fully functional and intercellular spaces have not yet developed. Older foliage is also relatively resistant because of reduced gas exchange (Patterson 1991) and increased suberization of cell walls (Evans and Miller 1972a, b). However, chronic air pollution stress on conifers is cumulative, and older age classes of needles have the greatest amount of injury (Miller et al. 1963, Pronos et al. 1978, Duriscoe and Stolte 1989).

Growth stage

Growth stage and foliage age within any growth stage also affect relative pollutant sensitivity (Miller et al. 1963, Coyne and Bingham 1982). Recently germinated seedlings are sometimes the most sensitive growth stage (Stolte 1982). The epigeous (cotyledons above the ground surface) conifers appear to be an especially sensitive plant group (Smith 1990). In species where the older age classes are sensitive to pollutants, seedlings are only slightly more sensitive than the older age classes (Miller 1977, Stolte 1982).

Other response factors

Ancillary biological, physical, and environmental measurements at a site are needed to evaluate the response of trees to pollution. Controlled fumigation exposures have provided insight into the role of environmental factors such as radiation, temperature, relative humidity, and soil moisture in plant responses to pollution (Heck et al. 1965, Taylor 1974, Huttunen 1984). These environmental factors affect pollutant response primarily by influencing stomatal functioning (Chapter 5). Miller et al. (1989; see also Chapter 12) found that available soil moisture at monitoring plots in the San Bernardino Mountains of southern California correlated with levels of crown injury. Correlations between other site factors and pollution injuries indicate that microsite differences in topography near point sources can influence the pollutant exposure of groups of trees (Carlson 1974, Hutchinson and Whitby 1976). River drainages, ridge tops, and saddles are topographic features that tend to enhance pollutant flux through conifer crowns, while ridges may block the flow of polluted air to other sites (see Chapter 3). Characteristics of the site, such as slope, aspect, elevation, percent bare rock, and species composition can be used to estimate relative temperature and moisture differences between sites. Site information on latitude and climatic information on winter minimums, as related to the morphology of conifer foliage, can aid in interpretations of pollutant stress on the forest.

Quality Assurance of the Measurement Process

The measurement process involves selection of the method(s), including sample collection and analysis, use of the method(s), and verification and validation of the resulting data. Measurement errors can be relatively large for subjective or complicated methods (Gumpertz et al. 1982, Cline et al. 1989). Measurement errors often are not quantified or reported, especially for many biological variables assessed during air pollution effects studies. Data collected with a faulty measurement process may lead to erroneous inferences about forest condition.

Faulty or poor quality data may result from inherent inaccuracies of methods (e.g., low repeatability), misapplication of the methods (e.g., deviation from standard protocols), and mismanagement of data (e.g., failure to check for transcription errors). Application of quality assurance procedures to the measurement process can reduce the collection of faulty data. Quality assurance is a system of activities designed to assure that products, services, or data meet stated standards of quality within stated levels of tolerance or uncertainty (Taylor 1985). Quality assurance includes quality control and quality assessment. Quality control represents all of the activities carried out to control the quality of the produced item as specified by the user or client. Important elements of quality control include selection and training of a competent staff, use of reliable instruments and raw materials, methods testing, development and use of standardized procedures, calibration, and control charting (Cline and Burkman 1989). Quality assessment consists of activities to assure that the quality control system is working properly. Key elements of quality assessment include internal checks such as systematic analysis of reference materials, and occasional checks by external sources, including equipment challenges and analysis of blind samples.

Data quality can be evaluated by the accuracy of identification of the property measured and the accuracy of quantification of that property (Taylor 1985). For example, the quality of data on visible foliar symptoms depends upon accurate identification of the type of injury (e.g., ozone injury versus winter desiccation) and the accurate quantification of the level of injury (e.g., 5% versus 20% of needle surface area). The accuracy of quantification (i.e., precision and bias) is an attempt to estimate the true value of a measurement property and always involves some level of uncertainty. Measurements are unacceptable unless the resulting data can be assigned a level of uncertainty within a stated probability. For example, Cline et al. (1989) reported that visual estimates of forest canopy condition at sites in a particular state or province (based on a system of 12 canopy condition classes) failed to meet a project precision goal of ±1 class deviation for 90% of the measurements on a plot when made by field crews from other states or provinces. In contrast, measurements made by crews from the state or province containing the study site met the precision goal. Thus, by comparing the precision of measurements made by two different types of crews, it was possible to determine which type of crew was more reliable for detecting real changes in forest canopy condition.

The objectives of individual research projects on pollutant effects influence the selection of methods used, including issues of time (e.g., sampling frequency) and space (e.g., number and types of sample sites, treatments, and observations). Ideally, the response variables that are the most indicative of air pollution stress are selected for measurement.

Appropriate techniques are characterized by the ability to assess key characteristics with 1) high selectivity (e.g., have unique or unambiguous responses to specific pollutants), 2) high sensitivity (consistently responds or measures a response at low concentrations), 3) high precision (measurements are reproducible), and 4) low bias (operates without artifacts such as contamination, loss, and calibration error) (Tingey et al. 1979, Taylor 1987). All of these characteristics are judged relative to the data requirements of the study. For example, a technique may not be the most precise of those available, but it can still be adequate relative to the precision needed to address the research question.

Written, standardized procedures are particularly important for difficult methods (e.g., foliar injury assessment), when multiple crews are collecting data, and when long-term data collection is envisioned (e.g., forest health monitoring). Proper execution of a measurement procedure involves operating the method in a "state of statistical control," which means that the measurement system is stable and data are reproducible within statistically defined limits. Statistical control is needed to evaluate the precision of a measurement process and is a prerequisite for estimating bias. Attainment and maintenance of statistical control is best verified with control charts, which ideally are real-time graphical plots of sequential test results in relation to statistically derived warning and control limits (usually ±2 and ±3 standard deviations, respectively) (Taylor 1987).

High quality data from a measurement system can be compromised by errors introduced during data handling and processing. Data handling errors can be particularly serious because they usually are not random, e.g., glitches in blocks of data, incorrect assignment of plot or treatment codes. Consequently, a systematic approach to data handling and database management is required, and data verification and validation procedures must be documented and checked as part of the quality assurance process.

Thorough documentation has both short- and long-term benefits to the project. In the short-term, documentation of research activities, events, and decisions that seem obvious or even trivial may turn out to be important to the proper interpretation of the data. In addition, the long-term integrity and usefulness of a research data set is increased greatly by thorough documentation, including journal publication of the methods separately or as part of the research results.

Methods for Evaluating Crown Condition

Visual estimates

The incidence and severity of foliar injury to Western conifers from air pollutants has been evaluated at the needle, whorl, branch, or tree level by visual observation of the foliage. The presence of injury on needles of different ages has been used as an indicator of the severity of injury at the branch and tree level (Pronos et al. 1978, Williams and Williams 1986); injury may take several years to appear if the dose (foliar uptake of ozone) is slight and may occur on current year's growth if the dose is high. The severity of injury has also been measured by visual estimate of the percentage of the total leaf area exhibiting air pollution injury. However, visible expression of pollutant injury may overlap with other abiotic (e.g., winter fleck) or biotic (e.g., scale) injuries that complicate visual estimates of percent cover. A greater degree of judgement on the part of the observer is required for this type of measurement as opposed to mere presence or absence, and the possibility for observer bias must be strictly controlled using quality assurance/control procedures, such as thorough training and an ongoing remeasurement program.

Measurements of the total leaf area affected by visible injury symptoms are more useful than simple presence or absence data because they correlate more closely with effects on photosynthesis, foliar water relations, and growth (Horsfall and Cowling 1978). Patterson and Rundel (1989) showed that the net photosynthesis of Jeffrey pines in the Sierra Nevada of California decreased as the percentage of leaf area with visible ozone injury increased (see Chapter 5).

Visual estimation of the relative proportions of areas of injured and uninjured foliage has been addressed by Horsfall and Barratt (1945). They demonstrated that the human eye was most perceptive at differentiating disease injury on foliage when the amount of injury discoloration was very small or very large compared with the surrounding colors. The Horsfall-Barratt system (Horsfall and Barratt 1945) of estimating plant disease divides the total range of injury percentages into twelve classes (Table 7.1) and is based on the logarithmic response of visual acuity (Horsfall and Cowling 1978).

Preliminary data on the relationship between percent chlorotic mottle and reductions in net photosynthesis (Figure 7.3) suggest that twelve classes of injury may be more than are needed to represent our current understanding of the biological significance of chlorotic mottle. Jeffrey pine trees in the Sierra Nevada with foliar ozone injury had an approximately linear decrease in net photosynthetic rates when percent chlorotic

mottle increased from 0 to approximately 30% of the leaf area. Chlorotic mottle injury above 30% of the surface area resulted in only minor further decreases in net photosynthetic rates.

Based on this information, a simplification of the Horsfall-Barratt system has been proposed for rating the severity of chlorotic mottle injury to Jeffrey and ponderosa pines in the West. The Western Pine Method (WPM; Stolte and Miller 1991) is the result of a multiagency collaboration (US Forest Service, National Park Service, and the California Air Resources Board) consisting of workshops and field tests. Severity of injury is scored in six injury classes (Table 7.1) using an arc-sine square root transformation of percentage data (Muir and McCune 1987). Retention of six injury classes gives WPM the flexibility to respond to improvements in our understanding of the relationships between visible injury and physiological responses of Western pines.

The precision and accuracy of visual estimates of foliar discoloration were investigated by Gumpertz et al. (1982) on four broadleaf crops. They found that the precision of three people who estimated total percent leaf area injured was high when compared with other sources of variation, particularly the variation in injury among the plants. Observations were most accurate when they could be compared with a quantifiable standard (obtained by overlaying a transparent grid on the leaves and counting the squares that fell over injured areas) and adjusted for observer bias. They pointed out, however, that this is necessary only if the desired precision has biological meaning. In many cases, the precision level for most visual estimates is greater than the corresponding biological response, such as the relationship between percent chlorotic mottle and reductions in net photosynthesis discussed above (Figure 7.3). They also concluded that estimating the percent injury of the three most injured leaves was a good predictor of the percent area injured of all leaves if the three most injured leaves were not completely injured (>95%). The proportion of leaves injured was not a good predictor of the percent area injured of all leaves.

In a field study of ozone-injured ponderosa pine, Muir and Armentano (1987) compared the results of foliar ozone injury evaluations made with pruned branches examined "in-hand" and remote assessments made with optical instruments (two types of binoculars and a spotting scope). They concluded that remote assessment methods did not yield sufficient precision and accuracy to warrant their use in describing severity of injury on an individual tree, and were only marginally appropriate in assessing stand or population mean values of injury severity. Poor correlations ($r^2 < 0.31$) between optical instruments and in-hand assessments (which were treated as "true" values) of foliar injury were found for most variables. Two experienced observers performed the in-hand

evaluation, and their results were found to be comparable; significant differences were found for estimates of needle length ($p=0.029$), but not for percent chlorosis ($p=0.446$), percent necrosis ($p=0.352$), percent other injury ($p=0.907$), and percent needle retention ($p=0.231$). This study suggests that visual estimates of injury severity have the highest quality when made with foliage in-hand and with known standards available for visual comparison, rather than with binoculars or whole-crown observations from a distance.

Spectral analyses

Spectral evaluation of air pollution impacts on vegetation has made rapid advancements in recent years as ground and airborne sensors have increased in spatial and spectral resolution. Spectral evaluation is based

Table 7.1 The Horsfall-Barratt system (Horsfall and Barratt 1945) for classifying visible injury on foliage is based on the logarithmic response of visual acuity and includes twelve injury classes. The Western Pine Method (WPM; Stolte and Miller 1991) has only six injury classes based on the relationship between the percentage of upper surface area of needles covered with chlorotic mottle and net photosynthesis in Jeffrey pine. See text for details.

Horsfall-Barratt Injury Class	Percent Injury	WPM Injury Class	Percent Chlorotic Mottle
1	0	1	0
2	1–3	2	1–6
3	4–6	3	7–25
4	7–12	4	26–50
5	13–25	5	51–75
6	26–50	6	76–100
7	51–75		
8	76–88		
9	89–94		
10	95–97		
11	98–99		
12	100		

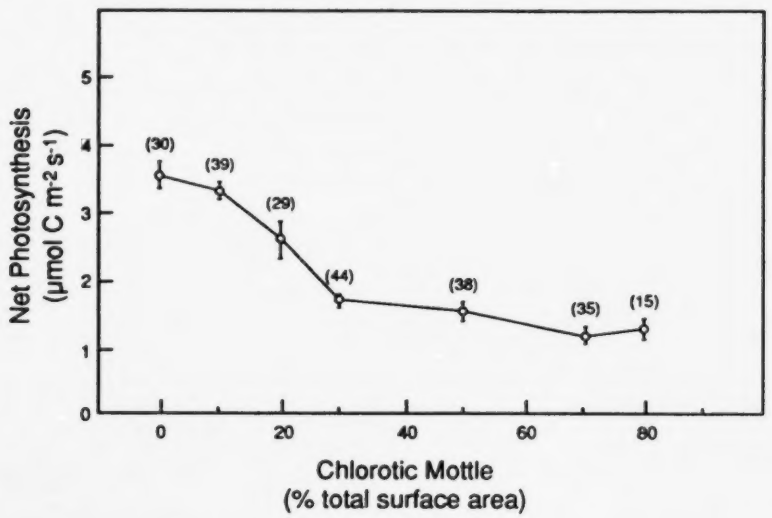


Figure 7.3 Relationship between photosynthetic rate of Jeffrey pine needles and percentage of needle surface area with ozone-induced chlorotic mottle. Numbers in parentheses are the number of measurement replicates. Adapted from Patterson (1991).

upon analysis of reflected electromagnetic radiation; these spectra vary by material based upon their chemical and structural composition. Use of airborne and satellite sensors to detect the effects of air pollution on forests is based upon predictable changes in the reflectance characteristics as foliage becomes chlorotic and senescent (Ustin et al. 1989). The ability to detect changes in chlorophyll concentration, water content, elemental content, and structural features of conifer needles before visible injury appears may allow detection of early stages of injury. Analyses of spectral reflectance in discrete bands or combinations of bands can give information on shifts in chlorophyll a and b ratios, the moisture content of the tissues, and other chemical compounds. Research is underway to develop techniques to improve the spatial resolution of remote sensing to evaluate individual tree canopies, differentiate pollutant-caused chlorosis from chlorosis due to natural senescence or other injuries, increase spectral sensitivity, and improve remote sensing of

mixed conifer stands under diverse topographical conditions. Spectral analysis of crown images would help to eliminate the subjectivity of human eye assessments.

Ustin et al. (1989) and Rock et al. (1986, 1988, 1989) have described methods for detection of air pollution injury to forests using spectral sensing techniques. They found that forest decline symptoms produce changes in the spectral properties of tree canopies, such as red and blue spectrum shifts, that may be detectable with high resolution spectrometry. More recently, camera and video capture of reflected electromagnetic radiation has been digitized for computer analysis. Camera and videographic techniques may improve estimates of foliage injury under field conditions and provide quality assurance and control audits of visual estimates. Additional research is needed to delineate the precision, accuracy, and cost of these methods. Remote sensing techniques are most valid when verified by extensive ground truthing using hands-on and binocular verification of tree crown conditions.

Remote sensing using visible or infrared spectral measurements has been used in a number of pollutant studies in the West to delineate pollutant injury over large areas. Carlson and Dewey (1972) used aerial photography (Ektachrome Aero film) to detect crown injury to conifers from fluoride where foliar fluoride levels exceeded 60 mg/kg (dry weight) and mortality of conifers where foliar fluoride levels exceeded 300 mg/kg. Larsh et al. (1970) used aerial photographs to establish the extent of ozone injury along a pollution gradient in the San Bernardino and San Gabriel Mountains of southern California.

Sampling of conifer crowns

When sampling branches from individual trees for symptom evaluation, it is important to minimize or account for the expected between or within-tree variance of symptom expression. The source of this variability includes between-tree genetic differences in sensitivity to pollution (Scholz et al. 1989), within-tree differences in shading of foliage, microhabitat differences in the availability of moisture and nutrients, and differences in micro-meteorology which may influence canopy exposure to pollutants (see Chapter 3).

Within-tree variance in foliar expression of ozone chlorotic mottle on 20 ponderosa pine trees was examined by Muir and Armentano (1987) in an area of the southern Sierra Nevada with moderate ozone injury symptoms (chlorotic mottle on the second or older whorls of needles; Pronos et al. 1978). They analyzed data on chlorotic mottle, necrosis, fascicle retention, needle length, and other injuries (biotic and abiotic) from hands-on evaluation of five pruned branchlets (smallest terminal leader

or side branch unit containing a full complement of needle whorls based on other branches in the same tree). They found that data from five branchlets was not sufficient to separate tree means ($p<0.05$) at a preset level of precision (usually 10%) selected for the sample area for any variable except necrosis because the within-tree variances were too great. Using an allowable error of 10% and a 95% confidence coefficent in a standard sample size formula (e.g., Snedecor and Cochran 1967), they estimated that the required sample sizes, including all whorls on each branchlet, for each measurement for a given level of precision (in parentheses) would be:

- chlorotic mottle (±10%), 8 branchlets
- necrosis (±10%), 3 branchlets
- needle retention (±10%), 42 branchlets
- needle length (±3 cm), 11 branchlets
- "other" injuries (±10%), 7 branchlets

These relatively large sample sizes (number of branchlets) may cause concern to field scientists interested in describing the crown condition of individual trees in natural stands. Pruning eight or more branchlets from a mature conifer can be difficult, and long-term monitoring of individual trees may lead to severe pruning of the lower crown foliage. The use of injury rating systems with fewer injury classes (e.g., Western Pine Method (six classes) instead of the Horsfall- Barratt system (twelve classes) (Table 7.1)), and the use of branch and tree level indices, should require fewer branchlets to define tree means, because the individual observations of branch symptoms will fall into fewer injury classes and result in less variance around the mean value of each branch. Additionally, indices emphasize common signals among symptoms and thus reduce the "noise" associated with the individual symptoms (Muir and McCune 1987). In most cases, researchers are interested in describing air pollution effects on stands of trees or on populations, and between-tree variances will be more important than the within-tree variances. Estimates of the between tree variances can be improved by sampling more trees per stand.

Whole-crown assessments in areas with slight to moderate injury, with or without optical aid, are a poor alternative to branch sampling (Innes 1988, Miller et al. 1989) because the correct diagnosis of the cause of foliage discoloration can only be accomplished with foliage in-hand. Whole crown assessments may be appropriate for smaller trees where the crown is readily visible without optical aid, or in areas of severe air pollution impacts where there is little doubt that an air pollutant is the cause of crown discoloration and pollution injury is severe.

Selection of branches from different portions of the tree crowns can be done systematically, randomly, or by stratification. Stolte and Bennett (1984) recommended sampling from the lower crown at the nearest branchlet at evenly spaced azimuths (for five branches these would be about 72° apart). Implementing this systematic approach was not always practical in the field (lower crowns of trees are particularly prone to variability in the spacing of branches) but provided a useful suggestion for addressing branch variation in the lower crown. In practice, most sampling is done randomly from a population of terminal, secondary, or tertiary branches distributed among the more accessible larger branches in the lower crown. The sampling of branches up to 15 m above the ground may be accomplished with some precision with a pole pruner. At greater heights, tree climbing, or less accurate means (rope saw, shotgun) may be necessary. The effects of pruning on the vigor of dominant and codominant conifers that exceed 0.1 m diameter at 1.4 m height should be negligible. Negative effects on carbon budgets are generally difficult to detect until 30% or more of the crown is removed (Muir and Armentano 1987). However, pruning of smaller, subdominant trees can more readily have negative effects, minimizing the usefulness of this canopy class for long-term monitoring.

Foliage longevity

In Western pine species, maximum foliage longevity ranges from two years for Monterey pine (*Pinus radiata*) to more than 40 years for bristlecone pine (*Pinus aristata*), and is related to the elevation at which the tree grows (Ewers and Schmidt 1982). In unpolluted environments in California and in the absence of other stresses affecting needle retention, ponderosa pines retain foliage for three to five years (a tree average of three to five annual whorls retained at any time) and Jeffrey pines six to eight years (Munz and Keck 1973).

Exposure to ozone can reduce the time of needle retention by ponderosa and Jeffrey pines. In a study by Miller and Van Doren (1982) in the San Bernardino Mountains of southern California, the number of needles or needle fascicles within reach of the evaluator were counted on the branches of 13 trees at each of five sites along a pollution gradient (west to east) over a three year period. There was a positive correlation between abscission rate and seasonal ozone dose (Figure 7.4). Abscission was most dramatic when visible needle injury had reached 80–90 percent of the needle surface area. In a study by Duriscoe and Stolte (1989), ponderosa and Jeffrey pines with severe chlorotic mottle retained three or fewer annual whorls of needles (Figure 7.5). Older whorls of needles abscised as younger whorls of needles became injured.

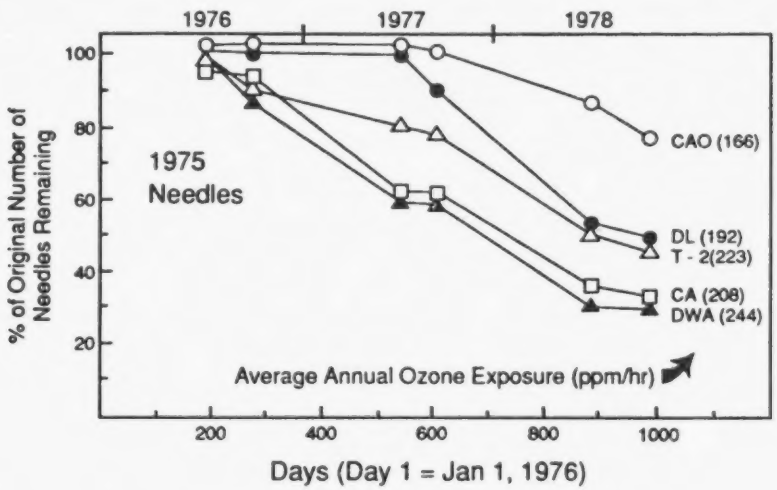


Figure 7.4 Percent abscission of 1975 needle age class in ponderosa and Jeffrey pine trees from 1976–1978 at five sites along a pollution gradient in the San Bernardino Mountains, California. Annual cumulative ozone exposures (ppm-hour) at each site are in parentheses; letters to the left of parentheses are plot identification codes. Adapted from Miller and Van Doren (1982).

Reduction in needle longevity is an indicator of air pollution stress for conifers when other factors leading to premature abscission of needles are eliminated or taken into account. Foliage longevity (Figure 7.6) may be determined by counting nodes (separation of whorls of needle fascicles produced each year), starting from the branch tip (most recent whorl) and proceeding to the last remaining whorl of needles (oldest whorl). Annual whorls are counted on branchlets (usually a more recent side branchlet) or on the main stem of seedlings or saplings. On most conifers, the annual "nodes" are relatively discrete and this type of measurement can be very objective and free of observer bias. A more precise quantification of the total foliage remaining on the branch may be made by estimating the percentage of the needle complement remaining within each whorl, in classes following the Horsfall-Barratt system, at systematic intervals (incremental percentages) (Stolte and Bennett 1984) or at coarser intervals (thirds or halves of the full whorl) (Stolte and Miller 1991). Additionally, length of the foliated portion of the branchlet has been used to describe needle longevity (Stolte and Miller 1991).

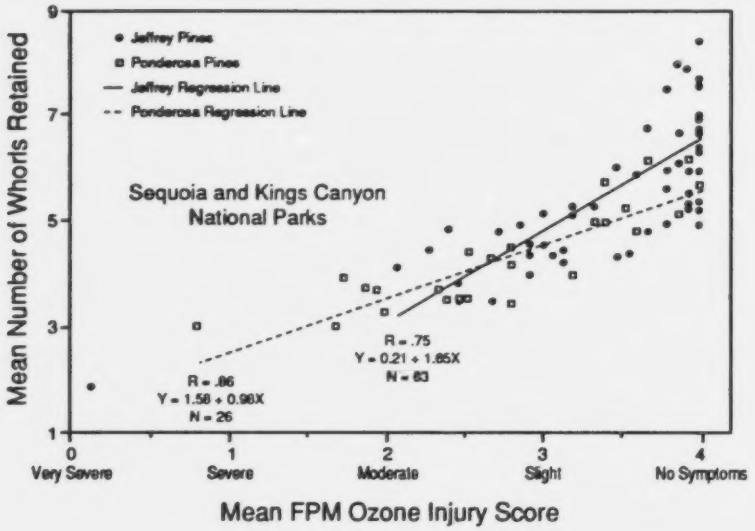


Figure 7.5 Relationship between severity of chlorotic mottle injury (mean FPM scores—low scores equal high injury) and retention of needle whorls for Jeffrey and ponderosa pines in Sequoia and Kings Canyon National Parks. Adapted from Duriscoe and Stolte (1989).

Crown vigor

The measurement of the quantity of live foliage through determination of the percentage of live crown can provide information on the degree of pollutant stress to an individual tree. Pine species typically self-prune the lowest branches as the trees grow, producing a crown form that is free of live branches in the lower third (or more) of the stem at maturity (particularly in more closed stands). Ozone stress to ponderosa and Jeffrey pines in the San Bernardino Mountains has a similar effect, decreasing the vertical length of the live crown (Parmeter and Miller 1968). Ozone-induced lower crown branch mortality is preceded by a decline in vigor of the lower crown that may be evidenced as a reduction in needle length (Parmeter et al. 1962, Miller et al. 1963) and the production of fewer numbers of needle fascicles (Miller et al. 1963, Ewell et al. 1989). The total dry weight foliar biomass of the current year foliage may be reduced by exposure to ozone (Miller 1977). Specific leaf weight of ponderosa pine needles can also be reduced, which may lower the photosynthetic capacity of needles (Coyne and Bingham 1981, 1982, Ewell et al. 1989). The appearance of shorter ponderosa pine needles in

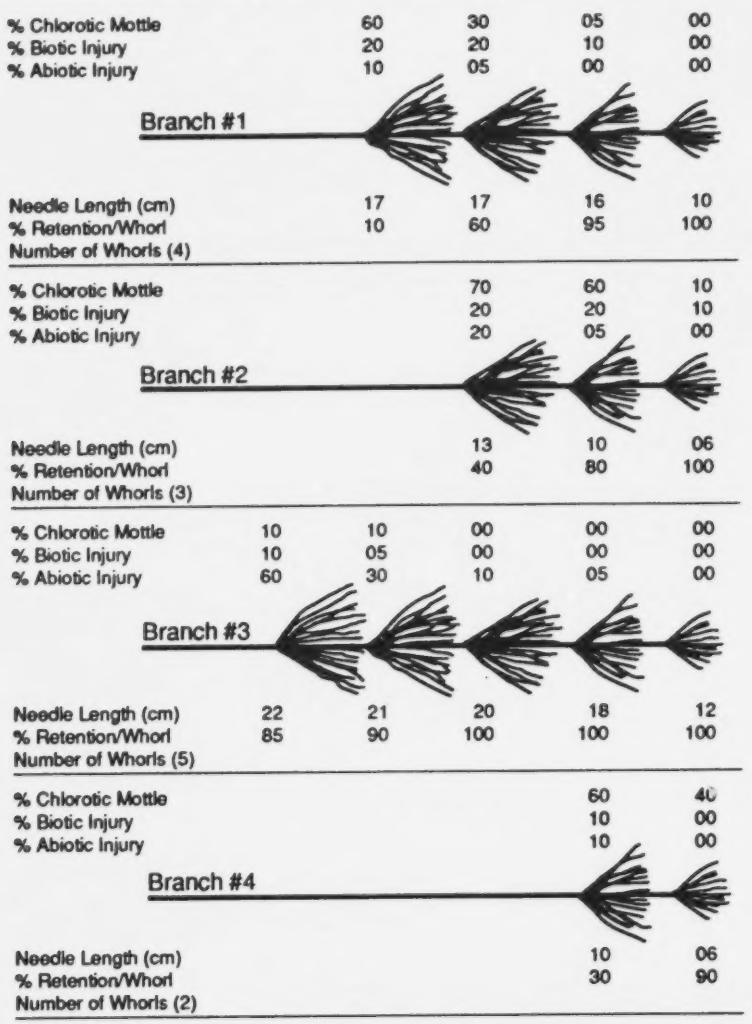

% Chlorotic Mottle 60 30 05 00
% Biotic Injury 20 20 10 00
% Abiotic Injury 10 05 00 00
Branch #1
Needle Length (cm) 17 17 16 10
% Retention/Whorl 10 60 95 100
Number of Whorls (4)
% Chlorotic Mottle 70 60 10
% Biotic Injury 20 20 10
% Abiotic Injury 20 05 00
Branch #2
Needle Length (cm) 13 10 06
% Retention/Whorl 40 80 100
Number of Whorls (3)
% Chlorotic Mottle 10 10 00 00 00
% Biotic Injury 10 05 00 00 00
% Abiotic Injury 60 30 10 05 00
Branch #3
Needle Length (cm) 22 21 20 18 12
% Retention/Whorl 85 90 100 100 100
Number of Whorls (5)
% Chlorotic Mottle 60 40
% Biotic Injury 10 00
% Abiotic Injury 10 00
Branch #4
Needle Length (cm) 10 06
% Retention/Whorl 30 90
Number of Whorls (2)

Figure 7.6 Example results from the measurement of air pollution impacts (chlorotic mottle, biotic injury, abiotic injury, needle length, percent fascicle retention on each year's whorls, and the number of whorls per branch) on ponderosa and Jeffrey pine branches. These variables can be evaluated separately or combined with whole crown evaluations (e.g., live crown ratio) into additive indexes to indicate the degree of pollution stress at the tree level. Drawings illustrate only the number of whorls retained. Adapted from Stolte and Bennett (1984).

the lower crown, relative to upper crown needle length, results from chronic exposure to ozone (Miller 1977). Axelrod et al. (1980) estimated the leaf area index for whole trees and found that severely injured trees had less than half the leaf area available for photosynthesis than slightly injured trees. These effects, combined with a decrease in foliage longevity of the remaining live branches, may lead to a drastic reduction in crown fullness or density, readily observed even at a distance (Figure 7.7).

Mortality of lower branches of pines from air pollution can be distinguished from branch mortality caused by limb rust (*Peridermium filamentosum*) because limb rust often starts at midcrown and progresses upward and downward (Walters 1978). Fluoride injury on Douglas-fir in Montana can cause high branch mortality at the apex of the trees, in contrast to the lower crown defoliation caused by sulfur dioxide (Carlson and Dewey 1972, Carlson 1974, Carlson and Hammer 1975) and ozone (Miller 1977, Duriscoe and Stolte 1989).

Indicators of crown vigor include needle length, number of fascicles per whorl, and foliar biomass, and may be measured from a sample of pruned branches, or from evaluations of reachable branches on saplings and open-grown mature trees. Another approach is whole-tree measurement of crown vigor using live crown ratio (or percent live crown) and crown density (Figure 7.8). Live crown ratio refers to the portion of the stem that has live branches relative to the portion of the stem without branches (Figure 7.8b). This may be visually estimated by an observer or measured using a clinometer or similar device. Reduced live crown ratios may indicate abnormal lower branch mortality resulting from air pollution stress, particularly if the live crown shows evidence of ozone stress as measured by the number of needle age classes retained, the severity of foliar discoloration on remaining whorls, and the shortness of the needles. Trees with dominant and co-dominant crown positions are most easily evaluated for live crown ratio. Sub-dominant trees already have reduced live crowns because of self-pruning due to shading.

Crown density, the fullness of the existing live crown, has also been visually estimated based on comparison of sample trees with a reference tree from the same stand, a reference photograph, or a reference drawing (Duriscoe 1987b, Innes 1988). The density of the whole crown can be evaluated or the upper and lower crowns can be evaluated individually (Figure 7.8c). Evaluation of both the upper and lower crowns may provide information on causal agents of crown thinning because certain agents, e.g., ozone, are likely to degrade the lower crown more rapidly than the upper crown. Crown assessments that combine observations on live crown ratio and crown density provide a more complete picture of crown vigor (Figure 7.8d).

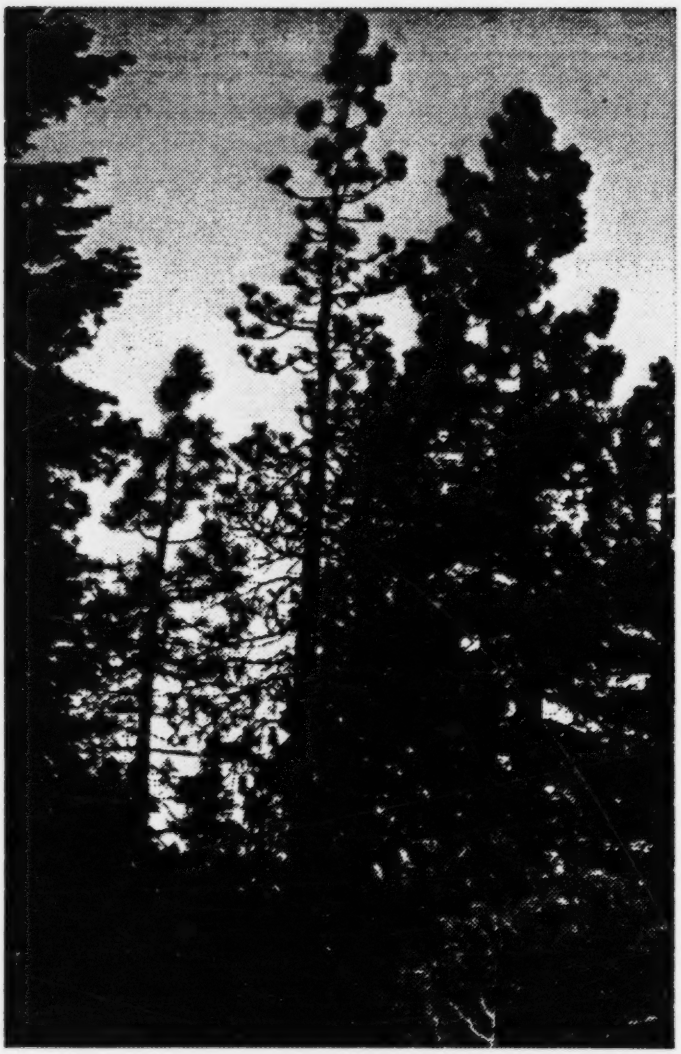


Figure 7.7 The effects of chronic ozone injury on crown vigor (center tree) reflected in needle retention, needle length, crown density and percent live crown on a symptomatic (ozone sensitive) ponderosa pine in the western United States. Asymptomatic (ozone tolerant) genotype of ponderosa pine (tree on right) with relatively good crown vigor.

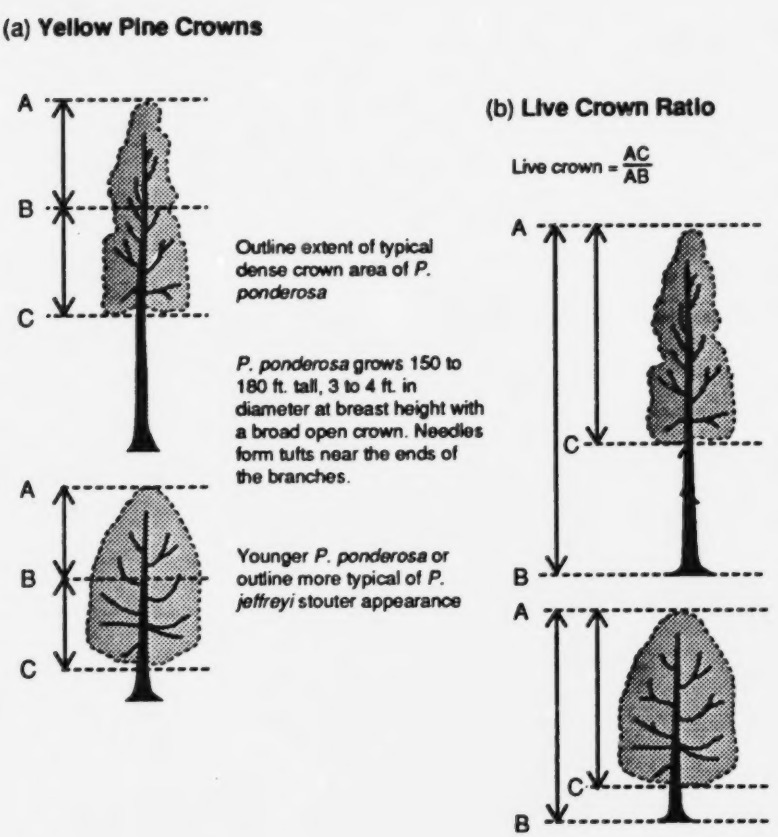

(a) Yellow Pine Crowns
A
B
C
Outline extent of typical dense crown area of P. ponderosa
P. ponderosa grows 150 to 180 ft. tall, 3 to 4 ft. in diameter at breast height with a broad open crown. Needles form tufts near the ends of the branches.
A
B
C
Younger P. ponderosa or outline more typical of P. jeffreyi stouter appearance
(b) Live Crown Ratio
Live crown = AC/AB
A
C
B
A
C
B

Figure 7.8 Rating whole crown vigor on ponderosa (PP) or Jeffrey (JP) pine trees in the western United States using crown density (CD) or live crown ratio (LCR) methods. (a) Habit of mature and younger PP or JP and the visual or measured delineation of the crown into upper (AB) and lower (BC) halves. (b) Mature and younger PP or JP and the delineation of live crown ratio (AC/AB). (c) Methods of rating upper and lower crown density on trees with different branching habits. (d) Crown density and live crown ratio measurements on PP or JP. Adapted from Duriscoe (1987b).

(c) Crown Density Rating

Estimate fullness and percentage of live branches in each half and assign a numerical rating on a scale of zero to ten.

(1) and (2) have different growth patterns, but the same relative density of foliage.

(1) many branches, thin foliage

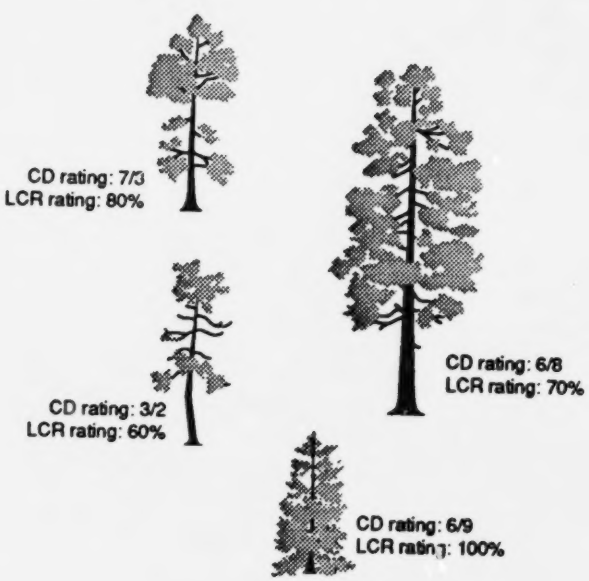
(2) fewer branches, fuller foliage

Numerical ratings for (3) and (4) depend on the species; that is, the greatest fulness, density, and shape typically found in that species.

(3) tall, thin

(4) short, stout

(d) Crown Density Rating
Live Crown Rating



Stem growth

Studies on ponderosa pine in southern California (Miller 1977, Miller et a'. 1989) and in the Sierra Nevada (Vogler 1982) have demonstrated a relationship between incremental growth of stems and tree sensitivity to ozone. The radial growth of stems (including the bark) can be measured using a forester's stem diameter tape, while vertical growth of saplings can be measured between branch nodes on the main stem. Miller et al. (1989) found that the relative diameter growth of the boles of symptomatic ponderosa pines and Jeffrey pines in the San Bernardino Mountains was less than asymptomatic trees of the same size class. Radial growth assessments, without radial ring width determinations, can only be made by repeated measurements on the same trees (e.g., trees in plots). Trees to be remeasured for diameters can be precisely relocated by attaching a numbered tree tag with a nail. Vogler (1982) found that the incremental height growth of symptomatic ponderosa pine saplings growing in the Sierra Nevada was reduced relative to asymptomatic saplings in the same stand. The apical leaders of severely injured ponderosa pines in the San Bernardino Mountains have been observed growing horizontally while under no obvious light stress conditions (Miller 1973). Height growth can be evaluated by repeated annual measurements using a height pole or clinometer. Incremental growth of stem leaders of saplings can be measured using a height pole or clinometer, by repeated measurements of total height, or by measurements of annual height increments between major branch whorls.

Tree-level injury indices

Observations of crown response variables made at different levels of biological organization may be compiled in an index to describe the severity of pollution injury to a particular tree (Muir and McCune 1987). Because trees are a fundamental biological unit of forest ecosystems, most injury response variables are appropriately summarized at this level and then summarized at the plot or stand level to give information on the incidence and severity of injury. Indices can be used to quantify pollution stress, estimate the potential for growth effects, and reduce statistical "noise" associated with individual symptoms (e.g., reduce the number of sample branches required for measuring foliar variables as discussed earlier in this chapter). Indices can weight symptoms according to their importance in diagnosing air pollution response and in estimating potential growth and physiological effects. Ideal indices produce high correlations between crown response variables and ambient pollutant doses. Atmospheric monitoring of ambient concentrations of pollutants is generally sparse in Western forests (Chapter 3), so assessments of crown injury may help delineate relative pollution concentration gradients.

Controlled exposure studies and field studies of ozone injury on ponderosa and Jeffrey pines have led to the development of several ozone injury indices. An additive index known as the Oxidant Injury Score (OIS) was developed to monitor crown condition in permanent plots in the San Bernardino Mountains of southern California in the early 1970's (Miller et al. 1989). The index combines data from binocular evaluations of needle discoloration, longevity, and relative length in the upper and lower crowns with visual evaluations of lower branch mortality. The OIS index is additive (data from all variables are added together) and foliage longevity receives the greatest weight. Lower scores indicate more severe injury; a tree with a score of 0 is dead while trees with scores of 36 and greater have no symptoms of ozone injury. Plot-level averages of OIS values have correlated well with measurements of ozone concentrations in mountainous terrain in southern California (Miller 1977).

In the Sierra Nevada, US Forest Service pathologists initiated the monitoring of trends in ozone injury to ponderosa and Jeffrey pines by establishing an extensive network of plots in 1974 (Pronos et al. 1978, Vogler 1982, Allison 1984, Williams and Williams 1986). They used a basic tree-level index, the Forest Pest Management (FPM) index, that determines the number of annual whorls free of chlorotic mottle. The FPM index score is low for severely injured trees, similar to the OIS index. Trees are assumed to have no significant ozone injury if they possess four or more annual whorls with no chlorotic mottle on the youngest four whorls. Partial whorls retained (less than 100% fascicle retention per whorl) are counted as whole whorls. Five different scores are possible: 4, 3, 2, 1, and 0 (4 = 4 or more annual whorls free of ozone injury; 0 = no annual whorls free of chlorotic mottle).

The National Park Service (NPS) devised a method for measuring the crown condition of pines in survey and permanent plots (Stolte and Bennett 1984). The method calls for evaluating variables, measured at the whorl, branch, and tree level, that are affected directly or indirectly by ozone. The whorl and branch level variables are measured from five pruned branches from the lower crown of trees of all size classes and include:

- percent foliar surface area with chlorotic mottle
- percent surface area with necrosis
- percent surface area with other injury (biotic and abiotic)
- modal needle length per whorl
- percent needle fascicles remaining per whorl
- number of whorls per branch

The tree level variables are:

- percent live crown ratio
- cone crop (1–10 scale)
- type and severity of bole injury (1–10 scale)
- bole diameter at breast height

The NPS variables are then combined in a nonadditive index to give a tree level score for the amount of ozone injury. Tree level scores are then averaged (n=15) to give plot level scores.

Using the NPS methods for data collection, Duriscoe (1991) devised an additive index known as the Eridanus Injury Index (EII). The EII has been used in quantifying ozone effects on pines in the West by the US Forest Service, National Park Service, and the California Air Resources Board. The EII possesses all the desirable characteristics for injury indices established by Muir and McCune (1987), and has been modified and described as part of the Western Pine Method (Stolte and Miller 1991). It is a composite score consisting of four parameters representing the four main effects of ozone on pines:

- Whorl retention: increased senescence of needles and reduced whorl retention that reduces the amount of carbon fixation;
- Chlorotic mottle: the appearance of chlorotic mottle symptoms on remaining needles that further reduces photosynthesis;
- Percent live crown: reduced live crown ratio as lower branches die first in declining trees; and
- Needle length: reduced needle length of emergent needles as carbon reserves become limiting.

The relative contribution of each parameter to the composite score is weighted based on its relative importance to carbon fixation and growth. Whorl retention receives the greatest weighting, with chlorotic mottle, percent live crown, and needle length receiving proportionately less weight. The index has a range of 0 to 100 (0 = a tree with no chlorotic mottle; 100 = a severely injured tree retaining only the current year's foliage, more than 75% of the foliar area with chlorotic mottle, an average modal needle length of less than 1 cm, and a percent live crown of 10% or less). A tree must have at least a trace of chlorotic mottle to receive a non-zero score, regardless of the condition of the crown.

Population and Community Responses

Crown condition assessments of individual trees may encompass many stands to detect the effects of air pollutants on populations of trees; evaluations of forest condition over large areas are commonly called surveys. A survey frequently consists of a snap-shot sample of a forest population with the intent of describing the incidence and severity of air pollution effects. Surveys are particularly useful in describing the spatial distribution of injury within the total areal extent of the population. With no intention to resample, it is not necessary to tag and map trees and sites. Data from surveys designed to estimate spatial extent can not be used to deduce temporal trends.

Surveys may be developed into a system of plots to be monitored for trends over time (Figure 7.9) (Miller 1977, Duriscoe and Stolte 1989, Miller et al. 1989; see Chapter 12). Plots are relocatable areas containing systematically or randomly selected individual trees within a defined area (fixed or variable size). Plots in forests have traditionally been located and relocated from site descriptions, photographs, and topographical maps. Land navigation systems such as the LORAN (land-based radio signals) or Global Positioning Systems (GPS) (satellite emitted radio signals) have had only limited use in locating plots, but this use should increase in the future as more satellites are put into orbit and the cost of instruments decreases.

Assessing Responses of Populations

The initial steps in selecting methods for assessing air pollution effects on forest stands are to develop the hypotheses to be tested, determine the growth stage(s) of each species to be evaluated, ascertain the nature and concentration of the ambient pollutant(s) of concern, and delineate the response variables to be measured. In many Western studies, the focus of the research has been on the mature growth stages of pollutant-sensitive species at sites along sharp (point source) or gradual (regional) pollutant gradients. The response variables most often evaluated were:

- presence, severity, and incidence of visible foliar injury;
- reduced retention of needles;
- accumulation of toxic substances in foliage;
- stem growth;
- resistance of the trees to natural biotic and abiotic stresses; and
- tree mortality.

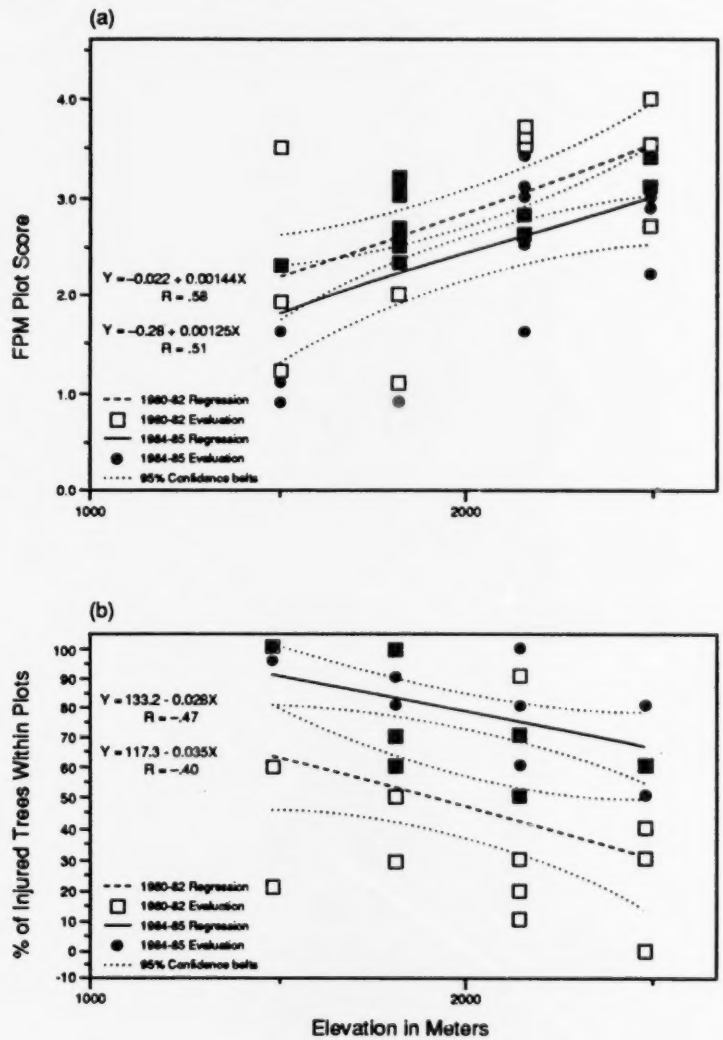


Figure 7.9 Trends in (a) the severity of ozone-induced foliar injury as measured by Forest Pest Management (FPM) scores (low scores equal high injury), and (b) the incidence of foliar injury on ponderosa and Jeffrey pines in plots at different elevations in Sequoia and Kings Canyon National Parks in 1980–82 and 1984–85. Dramatic increases in the incidence of injury were observed between the two periods. From Duriscoe and Stolte (1989).

Other injury responses such as altered needle growth, increased branch mortality, and reduced live crown ratio or density have also been measured (Pronos et al. 1978, Miller 1989, Duriscoe and Stolte 1989, Ewell et al. 1989, Miller et al. 1989). The hypotheses focused on the nature, severity, and incidence of injury; spatial and temporal trends in injury; relationships between pollutant injury and natural forest stresses; and the ecological ramifications of acute or chronic pollution injury (Miller 1977, Taylor 1974, 1980, Wellburn 1989, Smith 1990).

Area sampling and survey designs

The sampling of trees within forests is a critical element in the accurate quantification of the condition of the population. Procedures for sampling spatial phenomena are described in reference texts on the subject (e.g., Haggett et al. 1977, Taylor 1977). Six basic methods are available: systematic, simple random, stratified random, stratified systematic unaligned, multistage, and multifactor. Forest plots or survey points have traditionally used the systematic design in forest health surveys (Innes 1988). While systematic sampling with an appropriately small grid size may yield a very accurate estimate of the true population values, it may not be the most efficient method. If prior knowledge of the population is available, a stratified sample will usually yield comparable or better accuracy for less effort (Taylor 1977).

The distribution of tree species within the forest area is a fundamental spatial factor known to most forest managers. This information may be derived from vegetation type maps or a Geographic Information System (GIS) and used as the first level of stratification, defining the target population. Some type of randomization of point locations and tree selection within plots should be employed when locating survey or plot sites, as random samples have the advantage of being independent of one another, a desirable characteristic for many statistical procedures. Simple random sampling of the target population, however, allows the possibility of large contiguous areas being left out of the sample and thus limiting spatial resolution of the data. As a compromise, a spatially stratified random sample outlines the target population or sites where the species of interest occurs (Figure 7.10). After defining the target population and species to be evaluated, a systematic grid may divide the area to be sampled into a given number of equal areas, and a random point is selected within each grid square that contains a specified areal coverage of the target species (Figure 7.10a). This method allows for the quantification of the incidence, severity, and spatial extent of the crown response variable(s) measured (Figure 7.10b) (Duriscoe 1990).

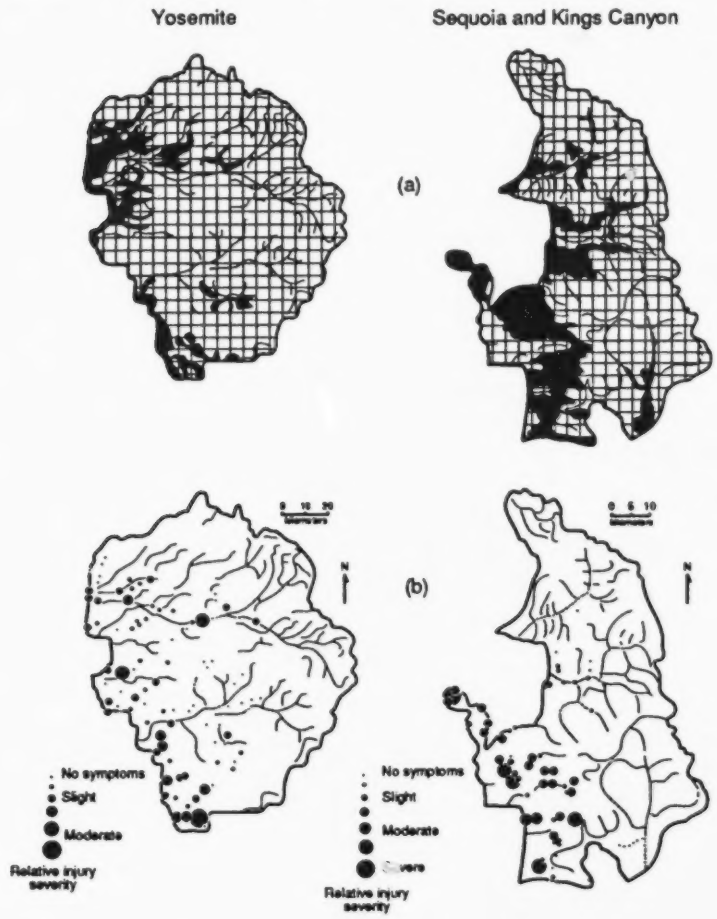


Figure 7.10 Stratified random sampling design for evaluating air pollution injury on ponderosa and Jeffrey pine trees in Sequoia and Kings Canyon National Parks and Yosemite National Park. (a) Distribution of mixed conifer type containing ponderosa and Jeffrey pine overlaid with a 3.2 km density grid. Trees were scored for ozone injury at randomly selected sample points within the grid units containing the mixed conifer type. (b) Distribution of the severity of ozone injury on ponderosa and Jeffrey pines in both parks (note that injury severity scales are different for each park). From Duriscoe and Stolte (1989).

Further levels of stratification have been based on knowledge of the spatial distribution of air pollutant(s) concentrations and durations. In many air pollution-forest response studies the objectives are to examine trends in effects along a pollution gradient (measured or inferred) (Miller 1977, Miller et al. 1989, Chapters 8–12 in this volume), or to compare impacted areas (based on the assessment of crown response variables) with areas that are relatively free of pollution impacts (Peterson et al. 1987, 1989; Chapter 11). In complex mountain areas, topography strongly influences the mixing of air and transport patterns of pollutants into the forests (Chapter 3). Portions of drainage basins may respond differently, so stratification into relatively similar groupings may be helpful. Evaluating pollution injury by drainage basin may be an appropriate method to obtain a more accurate estimate of the response of the entire population. Duriscoe (1990) found large differences in the severity and incidence of injury to the crowns of ponderosa and Jeffrey pines in different river basins in Sequoia and Kings Canyon National Parks in California.

The type of survey depends on the nature and source of the pollutant (regional or point-source). In surveys designed to evaluate the effects of a regional pollutant such as ozone on a major forest area (Miller et al. 1989, Duriscoe 1990), the stratified random design is very effective at determining incidence, severity, and spatial extent of injury (Arbaugh et al. 1991). Near point sources, stratified random sampling (using smaller grids) is sometimes used, but more typically radial transects (Figure 7.11) (Carlson and Dewey 1972, Severson et al. 1990) or less frequently zonal methods (Figure 7.12) (Gordon 1974, Carlson 1974) are used to map the severity, incidence, and extent of injury around sources of fluorides, sulfur oxides, or toxic metals (Carlson and Hammer 1975, Bunce 1979, 1984).

Variations in environmental factors that influence the response of trees to pollutants may be controlled by stratifying the sample to include only certain micro-site types, such as south-facing, open-grown stands. If this information is available on a population-wide level, this method may reduce the statistical static resulting from the inherent variability of the population. Of course, conclusions based upon a stratified sample apply only to the portion of the population sampled, just as population samples apply only to the whole and not to selected subsets. For example, Duriscoe and Stitt (1990) used a stratified-random sample design to evaluate the accumulation of sulfur and toxic metals in relation to the subalpine fir population growing within the boundaries of North Cascades National Park Complex. The areal extent of subalpine fir was identified using digitized information on a GIS. Further stratifications of the subalpine fir population using the GIS included only open canopy stands, south-to-west facing aspects, and slopes less than 80%. The stratified stands were then located in seven smaller areas based on

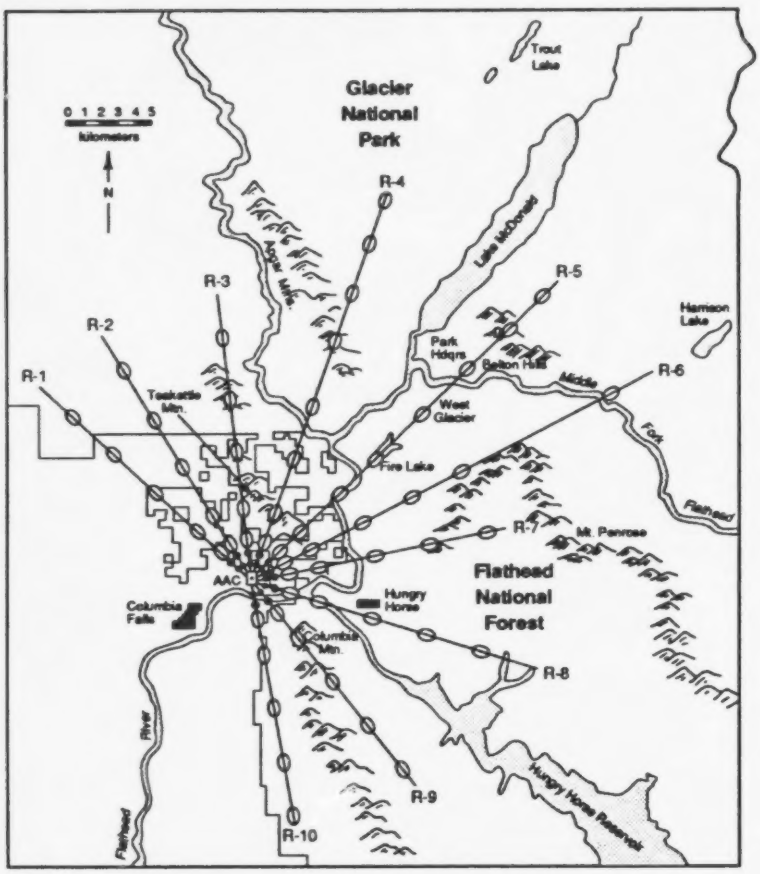


Figure 7.11 Radial transect sampling design to detect the impacts of fluoride emissions from the Anaconda Aluminum Company (AAC) on the surrounding mixed conifer forests in Montana. Fluoride concentrations in trees and other biological targets at the sample points (circles) on transect lines were used to construct pollution isopleths. Adapted from Carlson and Dewey (1972).

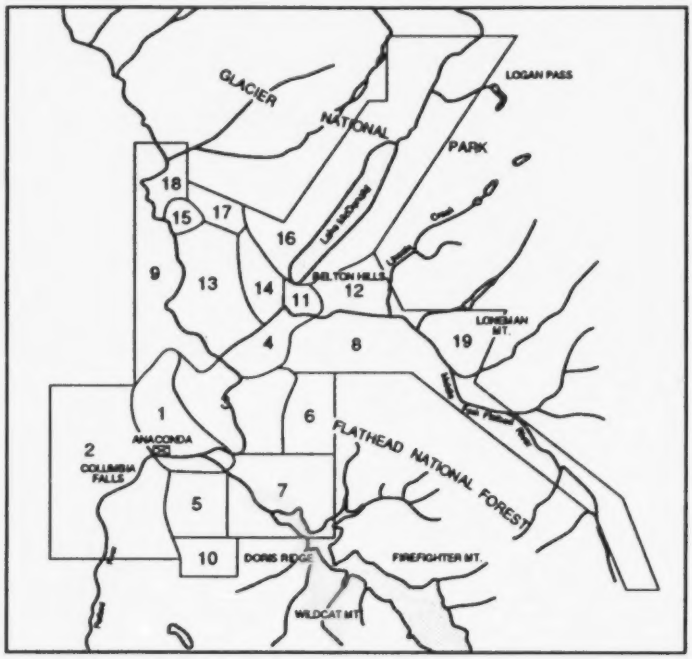


Figure 7.12 Zonal sampling design to evaluate the impacts of fluoride emissions from the Anaconda Aluminum Company (⊠) on the surrounding mixed conifer forests. Same area as in Figure 7.10. Adapted from Gordon (1974).

topography to delineate the seven primary water drainage basins in the area. Air basins were assumed to be the same as the water basins in this area of mountainous topography. Three potential sample points were then selected at random from the population of stratified stands in each of the seven air basins. This method gave every stratified stand within each drainage basin area an equal chance of being selected, maintained some degree of spatial resolution, and allowed for a means of differentiating air pollution deposition and uptake between drainage basins.

Sample size

The number of samples required to estimate the incidence and severity of air pollution effects on the crowns of a population of trees depends on the following: the allowable error of the estimate (the confidence inter-

val), the probability that the true population value will lie within the bounds of the confidence interval (the confidence coefficient), and the actual proportion of injured trees (p—for incidence) or natural variability (σ^2—for severity) in the population. The first two factors are set by the researcher, and may be based on research objectives and available resources, while the latter factors may be determined by estimation from previously collected data or a theoretical consideration of the "worst case."

Incidence is the frequency of occurrence of a variable such as the number of injured trees in a stand. Incidence is an important statistic in areas of low pollution exposure or in wilderness areas where the existence of any trees showing visible pollution injury, even if the injury is very low in severity, may be interpreted as a significant deterioration of resource values. Inferences made about proportions are based on binomial sampling as described in various statistical texts (e.g., Snedecor and Cochran 1967, Box et al. 1978). Assumptions which must be met to use binomial sampling theory are that observations should be random, independent, and from a population of infinite size (about 400+ individual trees in practice). If an objective of a study is to identify the incidence of injury in stands of less than 400 trees, total enumeration should be considered rather than sampling.

The peculiarities of the binomial distribution are such that the greatest numbers of samples are required when the true proportion (p) of injured trees in the population is 0.5 for a given allowable error in the estimate (half-width of the confidence interval = d) and the confidence coefficient. Table 7.2 illustrates the required sample sizes for estimating selected values of p using a 95% confidence coefficient and one of three different values for d. It is apparent that if the true value of p is completely unknown, at least 100 observations should be taken to ensure an estimate with a precision of ±0.10 or 10%.

The measurement of intensity of injury to populations may be estimated by multiplying the mean severity of injury to the injured portion of the population by the incidence of injury. Various indicators of injury severity may be used, such as foliage retention or percent leaf area covered with visible damage, but data forming highly skewed distributions should be avoided in order to apply parametric statistics in the analyses. A synthetic index such as the EII will usually satisfy this condition. The required sample size for estimating the mean severity of injury to the injured portion of the population may then be calculated using the following equation (e.g., Snedecor and Cochran 1967):

Table 7.2 The effect of differences in the true proportion (p) of injured trees in a population on the sample size required to estimate p with a given allowable error (d, equal to the half-width of the confidence interval) and a 95% confidence coefficient. Derived from Box et al. (1978)

Allowable error (d)	Approximate number of samples required for p=						
	0.05	0.10	0.20	0.50	0.80	0.90	0.95
0.05	130	200	350	400	350	200	130
0.10	45	60	80	100	80	60	45
0.15	30	35	40	45	40	35	30

$$n=(Z^2 * \sigma^2)/d^2 \qquad \text{(Equation 7.1)}$$

where

σ^2 = the population variance

Z = 1.96 (critical value of standard normal Z and confidence coefficient of 95%)

d = the allowable error in the sample estimate (half-width of the confidence interval)

The use of Table 7.2 and Equation 7.1 may be illustrated using the following "worst case," which is based upon studies in the Sierra Nevada (Duriscoe 1991). Prior knowledge of the worst case suggests that 50% of the trees will be injured and that the injured trees will have a mean injury index of 50 (0 to 100 scale) with a population standard deviation (σ) of 15. The sample size required to estimate the incidence of injury in the population (confidence interval ±0.05 or 5%, confidence coefficient 95%) would be 400 trees (Table 7.2). For severity, if we require a confidence interval of ±5 index units (5% of the total range) and a 95% confidence coefficient for an estimated population value, 35 *injured* trees must be sampled (Equation 7.1). In this example, when analogous half-widths of the confidence interval (5 units out of 100) are used in each calculation, far more samples are required to accurately estimate the incidence of injury in a population than to estimate the mean severity of injury to the injured portion of the population.

It is often necessary to identify differences in the incidence or severity of injury between populations or within a population over time. This usually involves statistical testing, wherein two or more mean injury levels are compared, and requires that sample sizes be determined using equations other than Equation 7.1 (e.g., chapter 6 in Snedecor and Cochran 1967). Alternatively, the sample size needed to differentiate among sample means by a set difference can be determined through the results of sampling studies. For example, in a study of ponderosa and Jeffrey pine, Duriscoe (1991) determined the number of sample trees required per plot to differentiate among high, moderate, and low levels of ozone injury using plot-level averages of EII injury index scores and a confidence coefficient of 95%. Approximately 30 trees per plot needed to be sampled to detect a statistical difference of 10–15 units among the mean EII scores (Figure 7.13). Only small increases in precision were gained by sampling more than 30 trees in each plot.

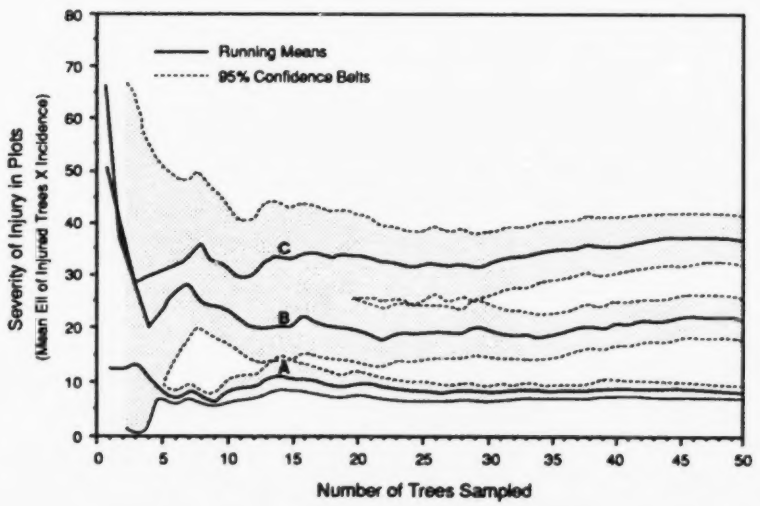


Figure 7.13 Running means of injury severity index (solid lines) and 95% confidence intervals (shaded areas) for single plots with (a) slight, (b) moderate, and (c) severe pollution injury. Sample sizes of at least 30 trees per plot are recommended to differentiate injury classes between plots or changes in the mean injury level within a plot over time. Adapted from Duriscoe (1991).

Summarizing results

Incidence of foliar injury (Pronos et al. 1978, Williams and Williams 1986) or an injury index combining severity of injury to individuals with incidence of injury can both be used as measures of injury to a population. However, important information can be lost when data are summarized as a single index value. In many cases it is desirable to report the distribution of individuals among injury classes as well as the synthetic indices.

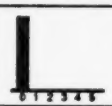
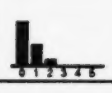
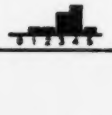
For example, Table 7.3 presents hypothetical data on the incidence and severity of injury in 8 different populations of ponderosa or Jeffrey pine. Injury scores are tallied in one of six injury classes numbered 0 to 5 (low to high pollution injury), and then compared using frequency histograms. Increasing population injury is indicated by a shift in the peaks of the histogram from left to right. The histograms illustrate differences in the condition of populations that have very similar injury index scores.

Assessing Effects on Communities

Determination of mortality due to chronic air pollution can be accomplished by monitoring individual trees in plots over time. Chronic exposures to high levels of air pollutants ultimately result in degradation of plant communities. As increasing numbers of sensitive genotypes of pollutant-sensitive species are killed, shifts in the composition and structure of plant communities may occur. Severe injury to individuals (Figure 7.7) does not always translate into detectable effects at the community level (Chapter 6), since impairment of some individuals may be compensated for by increased functioning of other individuals (e.g., release of neighbors following gap formation). In most cases, however, as pollutant deposition continues, more individuals of sensitive species are affected and more tolerant species begin to show evidence of pollutant stress. In extreme cases, gene pools are altered, mineral cycling is affected, insect, fire, and other stress cycles are altered, and successional patterns change (Miller 1977, Smith 1990).

The most serious effect of air pollution on conifer communities has been the degradation of forests around point sources. Intensive sampling using arithmetic or geometric transects, grids, or zonal sampling designs around point sources can elucidate the pronounced injury and mortality gradients that often occur around these pollutant sources. Stands of conifers close to the site (often within a 5–10 km radius) may have high mortality rates, leading to devegetation of the site. More commonly, severely impacted conifer communities near point sources of pollutants experience destruction of the more pollutant-sensitive species but remain vegetated by the more pollutant-tolerant species. This relationship is a

Table 7.3 Method of describing injury severity of trees in plots or populations using hypothetical data, based on the incidence of injury in six injury classes. Incidence of injury in all injury classes is multiplied by the mean injury index to produce a weighted injury index (data for calculation of mean injury index not shown). Injury class 0 = no injury, 1 = very slight, 2 = slight, 3 = moderate, 4 = severe, 5 = very severe.

Trees per injury class (100 trees per sample)									
Class 0	Class 1	Class 2	Class 3	Class 4	Class 5	Frequency distribution of injury	Mean injury index (injured trees only)	Incidence of injury (%)	Weighted injury index (population)
100	0	0	0	0	0		—	0	—
90	10	0	0	0	0		12	10	1.2
60	30	10	0	0	0		18	40	7.2
30	20	30	20	0	0		30	70	21.0
20	10	20	40	10	0		50	80	40.0
0	10	20	50	20	0		65	100	65.0
10	10	20	30	20	10		65	90	58.5
0	10	10	30	40	10		75	100	75.0

function of the nature and concentration of the air pollutant(s) emitted at the site (Carlson and Dewey 1972, Carlson 1974, Gordon 1974, Carlson and Hammer 1975, Bunce 1979, 1984).

Van Hook (1974) studied the effects of fluoride emissions from a phosphate plant in Montana by sampling along 12 radial transects centered on the plant. This approach is particularly appropriate if little is known about the prevailing wind patterns in the area. Van Hook found decreasing levels of fluoride in the foliage of conifers, in the soils, and in forage grasses with increasing distance from the source. Bunce (1979) utilized a grid design to locate 64 plots within the fume zone of an aluminum smelter in British Columbia to determine the effects of fluoride emissions on the radial ring growth of hemlock trees. Stem diameters and heights were also measured and foliage fluoride concentrations were determined. He estimated that 2,700 m^3 of wood were lost annually from 1954–1976 due to the operation of the smelter. Although the smelter caused a decrease in wood production, species regeneration within the impacted zone of the forest was unaffected.

Taylor et al. (1986) used a radial transect sampling design to evaluate the effects of chronic ozone (regional source—San Joaquin Valley of central California) and sulfur oxides (point source—an oil extraction facility in Bakersfield, California) on the crown condition of ponderosa and Jeffrey pines, the concentration of sulfur in the associated soil horizons, and the concentration of sulfur in associated lichen species in the southern Sierra Nevada. They found that concentrations of extractable sulfate in the 0–5 cm horizon decreased with elevation and distance from the source. A similar trend was observed for total sulfur in the foliage of pine needles and lichens. Crown condition assessments indicated that trees in plots nearest the valley had more visible foliar discoloration and the lowest retention of needle fascicles.

Determination of air pollutants as the causal agent of conifer community degradation can be a difficult process because subtle, chronic impacts of pollutants must be differentiated from the natural biotic and abiotic stresses on the trees and the natural successional processes that take place within the communities (Miller 1977, Treshow and Anderson 1989, Wellburn 1989, Smith 1990). Pollution effects on conifer communities from point sources are typically easier to identify and quantify because of the strong pollutant gradient surrounding point sources (National Research Council of Canada 1939, Whitby and Hutchinson 1974, Hutchinson and Whitby 1976). The most effective way of delineating chronic effects of pollutants is the examination of many variables using a variety of methods designed to differentiate pollutant effects from natural processes at different levels of biological organization. For example, evaluation of foliage for visible foliar discoloration (branch

level), the crown for patterns of dieback (tree level), and the foliar elemental content of different species (community level) would help to quantify fluoride stress on a conifer community near a point source. The establishment of long-term ecological monitoring plots is essential in elucidating the effects of chronic pollution on community structure.

The best documented case of regional air pollution causing serious impacts on Western conifers comes from the work of Paul Miller, US Forest Service, and associates in southern California (Chapter 12). This research included analyses of visual symptoms, physiology (photosynthesis and respiration), foliage retention and initiation, stem growth, susceptibility to pine beetles (*Dendroctonus brevicomis*) and root rot (*Fomes annosus*), nutrient cycling, cone production, and rates of mortality for ponderosa and Jeffrey pines to determine the effects of chronic oxidant (primarily ozone) exposure on a mixed-conifer forest. By evaluating the incidence and severity of ozone injury and mortality rates, they determined that impacts were greatest at plots closest to the Los Angeles air basin. Community analyses indicated that loss of pollutant-sensitive ponderosa and Jeffrey pines caused a shift in the plant community from an open canopy pine forest to a more closed-canopy oak-chaparral community.

Dendrochronology

This section provides an introduction to tree-ring analysis and a theoretical framework for the tree-ring studies of pollution impacts on forests that are presented later in this book (Chapters 8–11). To date, "no readily detectable, pollutant-specific single marker for identifying the effects of air pollution on forests or trees has been identified" (National Research Council 1989, p. 2). Yet, there are many non-specific indicators of stress that can detect anomalous growth patterns in trees, which could ultimately be related to air pollution. One such indicator, available in all temperate forests, is the annual tree-ring increment.

Tree rings are the only widely available source of long-term data on forest growth and productivity that may predate the present era of elevated atmospheric pollution. Year-to-year changes in ring width integrate past environmental and biological influences on tree growth, allowing detection of anomalous changes in tree rings that may be consistent with those expected from pollution stress.

Annual tree-ring increments can be analyzed in several ways for evidence of air pollution effects. These include using annual ring widths (e.g., Peterson et al. 1987, Johnson et al. 1988), ring areas (e.g., Hornbeck and Smith 1985, Phipps and Whiton 1988), and ring volumes (e.g.,

LeBlanc et al. 1987a, b), along with ring densities (e.g., Conkey 1988) and chemistry (e.g., Baes and McLaughlin 1984). The easiest measure of annual tree growth, and the one that will be emphasized here, is the radial ring-width series from the breast-height (1.4m) region of a tree.

Although tree-ring analysis based on breast-height ring-width series has obvious potential for the study of regional forest declines, its application in such studies has been difficult and controversial. One difficulty lies in the fact that tree rings are an integration of many environmental and biological influences on tree growth, including stand dynamics, tree maturation, and climate (Chapter 6). This means that any pollution signal may be small and embedded in a high level of natural environmental noise. The signal from air pollution may be weak relative to the noise of normal variations, giving low ratios of signal to noise. This problem is especially acute in the study of regional forest declines where air pollution levels are low compared to regions near pollution point-sources. Consequently, tree-ring studies of regional forest declines may need to examine hundreds or even thousands of ring-width series (e.g., Hornbeck and Smith 1985, Schweingruber 1986, McLaughlin et al. 1987) in order to reduce the noise level and increase the degrees-of-freedom for statistical tests.

Another difficulty is the lack of a generally applicable "normal" or expected growth model (c.f. Hyink and Zedaker 1987) for natural forests that can be used to identify abnormal growth patterns in trees. Such models are rare for all but the simplest cases, e.g., open-canopy forests and even-aged, single-species plantations. For mature closed-canopy forests, which are often a mixture of tree species and age classes, useful normal growth models rarely exist. In such environments, the evolution of tree rings through time is highly stochastic (Cook 1987b) and difficult to predict using deterministic, normal growth models.

Finally, what should an air pollution signal look like in tree rings? Anomalous reductions in ring-widths are not uniquely related to pollution effects on regional forest growth (Cook and Innes 1989). Current understanding of the physiological effects of various pollutants on tree growth is still poor, especially for relatively low doses (chronic exposures) of air pollution (see Chapter 5). There is also a lack of understanding of the interactions between pollution and climate, which may act synergistically or in opposition depending on the way in which climate is affecting tree growth at the time. Thus, without a good pollution response model for tree growth at the species level, there is little hope that tree-ring analysis can prove that pollution is directly responsible for a regional forest decline. Rather, tree-ring analysis is presently best suited for eliminating natural explanations of decline, such as climate,

stand dynamics and maturation, and for discovering anomalous properties in the data that are consistent with the intervention of some new stress such as air pollution.

Proper cross-dating of tree-ring data is a first step in analysis. As used here, cross-dating is a quality assurance/control procedure that applies to any application of radial increment data, wherein each tree ring is correctly dated to its calendar year of formation. It is also used to correct the dating for anomalies such as locally absent rings and false rings (sensu Fritts 1976) that would cause a simple ring count to be incorrect. Thus, cross-dating is synonymous with the correct dating and calendar-year alignment of tree-ring series. The mechanics and methods of cross-dating, along with much more comprehensive reviews of dendrochronological methods, are described in Fritts (1976), Hughes et al. (1982), and Cook and Kairiukstis (1990). Cross-dating is necessary to obtain accurate mean-value functions of tree rings computed from individual tree-ring series that are properly matched in time. Correlating misdated tree-ring data with climate data would produce biased results and potentially incorrect interpretations because of the dating errors in the tree-ring data. Cross-dating eliminates these sources of bias. This issue applies equally to both mean-value functions and individual radial tree-ring series. Both kinds of tree-ring data have been used for analyses of tree growth, as presented in chapters 8–11. Therefore, cross-dating should be regarded as the single most important quality assurance/control step in any dendrochronological study because the validity of all subsequent results and interpretations depend on correct cross-dating.

Another component of dendrochronology is site selection. Ideally, sites selected for tree-ring analyses should be based on an a priori set of criteria dictated by the scientific problem being investigated. For example, if climate is to be reconstructed from tree rings, then minimally-disturbed, climatically-stressed sites should be selected (Fritts 1976, Hughes et al. 1982). In the context of air pollution impacts on forests, site selection criteria might be determined by other factors such as the presence of air pollution pockets or gradients, the distribution of certain tree species sensitive to a particular air pollutant, and the spatial distribution of tree species or forests experiencing anomalous declines. Each of these criteria has been used in one way or another in the tree-ring applications described in other chapters in this book. A drawback to selecting sites based on criteria related directly to air pollution is that any result obtained from such analyses might be a biased representation of the overall health and vigor of the forest in which the sites are located. However, if the basic scientific problem is the documentation of a probable air pollution impact on the growth of a selected tree species,

then such restricted sampling is valid. For the more general problem of regional impacts of air pollution on forests, site selection using random sampling methods is statistically more powerful.

The selection of individual trees for sampling at a tree-ring site again depends on the nature of the study and the scientific question being addressed. For climate studies, trees showing obvious injury from insects, disease, or fire would not normally be sampled because such injuries could mimic or obscure the desired climatic signal in the tree rings. The same argument applies to the study of air pollution impacts on tree growth. However, certain air pollutants like ozone visibly affect the foliage of sensitive tree species and genotypes in known ways, primarily the accelerated abscission of needle whorls and the production of distinct visible foliar discoloration symptoms on some or all of the remaining needles. It is therefore possible to purposely sample both symptomatic (air pollutant sensitive) and asymptomatic (air pollutant tolerant) trees as part of an air pollution study directed at looking at growth effects within a species. The premise is that symptomatic trees will show a stronger air pollution signal in their ring widths if the air pollution stress is severe enough to overcome the inherent resiliency of the tree to loss of fixed carbon. This stratified sampling approach has been used by Peterson et al. (1987) in their study of Jeffrey pine and by Peterson and Arbaugh (Chapter 11) for ponderosa pine (var. *ponderosa*) in the Sierra Nevada. Alternatively, Graybill, Peterson and Arbaugh (Chapter 9) were not able to use this approach in their studies in the Colorado Front Range because of lower ozone concentrations (Chapter 3), the relatively higher tolerance of Rocky Mountain ponderosa pine (var. *scopulorum*) to ozone, and the subsequent lack of foliar injury symptoms that facilitate the identification of pollutant-sensitive and pollutant-tolerant individuals. Similarly, it is possible to stratify the sampled trees by crown dieback class in the hope that trees with more crown canopy dieback might be more severely impacted by air pollutants. Unfortunately, crown canopy dieback can be caused by both natural and anthropogenic factors, with the former being much more common and likely than the latter. Therefore, it is dangerous to assume and difficult to prove an air pollution effect on trees experiencing some form of generic canopy dieback.

A Model for Analyzing Tree Rings

A tree-ring series can be considered as a linear aggregate of several unobserved subseries or signals. This aggregate can be expressed as

$$R = A + C + dD1 + dD2 + E \qquad \text{(Equation 7.2)}$$

where:

R is the observed ring-width series n years in length;

A is the age and size related trend in ring width;

C is the yearly variation in ring width due to climate;

D1 is the change in growth due to endogenous disturbance;

D2 is the change in growth due to exogenous disturbance; and

E is the unexplained year-to-year variability not related to the other signals.

This model indicates the components that contribute to the observed tree ring without implying linear additivity. The d associated with D1 and D2 is a binary indicator of the presence (d=1) or absence (d=0) of either class of disturbance in the ring widths. Thus, A, C, and E are assumed to exist in R for all n years, although their relative contributions to the total variance of R may vary with time. In contrast, D1 and D2 are assumed to be present only if either disturbance has occurred at some time t0 in the life of the tree. And, in most cases, we should also expect the effect of either disturbance to eventually disappear in the ring widths. When both of these properties are fulfilled, a disturbance effect may be formally called a pulse to differentiate it from the continuous A, C, and E. There may, of course, be more than one disturbance of either kind in a tree-ring series.

In theory, an endogenous disturbance can be distinguished from an exogenous disturbance by comparing ring-width patterns of trees in a stand. Endogenous disturbances result from stand dynamics in which individual or small patches of canopy trees are removed by processes that do not affect the stand as a whole (Chapter 6). The development of canopy gaps creates patterns of suppression and release in the ring widths of surviving trees adjacent to the gaps. Trees away from these gaps show no response. Therefore, assuming that endogenous disturbances are random events in both space and time, D1 should be strictly contemporaneous only in the ring widths of trees adjacent to the same gap, but not elsewhere in the stand. In contrast, exogenous disturbances are assumed to affect large areas of forest simultaneously. The pertinent

feature of D2, then, is synchrony in time throughout the stand, which theoretically differentiates it from the temporal and spatial randomness of D1.

The impact of airborne chemicals on forest growth and productivity can be considered an exogenous disturbance if, for a given pollutant, the dose-response relationship is basically uniform across a sampled stand of trees. In describing the linear aggregate model in the context of forest-pollution studies, Cook (1987a) added a pollution term, dP, to Equation 7.2 to explicitly differentiate this kind of large scale anthropogenic disturbance from similar scale natural forest disturbances, such as those caused by insects, disease, and unusual meteorological events.

The growth trend A in Equation 7.2 is usually assumed to be a non-stationary process that reflects, in part, the geometrical constraint of adding a volume of wood each year to a stem of increasing radius and height. When this constraint is the principal source of the trend, A can often be modeled as a deterministic, negative exponential function of time (Fritts et al. 1969) having the form

$$A = a * e^{-bt+k} \qquad \text{(Equation 7.3)}$$

where a, b, and k are coefficients estimated from the data and t is time. This model is often appropriate for estimating the ring-width trends of trees growing in open-canopy forests where between-tree competition is minimal and natural disturbances are rare. It also assumes that the observed ring-width series begins after the juvenile period of increasing radial growth found in many conifers because Equation 7.3 is a monotonic function that strictly decreases to the limit k. For those ring-width series with an early juvenile growth period, a more general exponential function can be used (e.g., Warren 1980). Eriksson (1989) has criticized the asymptotic behavior of Equation 7.3 because it implies that ring widths do not diminish to zero in old trees as they senesce and approach death. However, for old-age conifers growing on semi-arid sites, Fritts et al. (1969) found that a standard negative exponential model with a zero asymptote (k=0) commonly underestimated the observed ring widths in the mature growth period.

From the form of Equation 7.3, it is clear that a negative trend in ring width is an expected property when competition and disturbances do not appreciably affect tree growth. Thus, considerable care must be taken to properly discriminate between decreasing ring widths due to increasing tree age and size and reductions in growth that may be caused by air pollution. Indeed, the identification of D2 in R (Equation 7.2) may be very difficult if D2 is only expressed as an added reduction in ring width and does not depart strongly from that estimated by A. However, when deterministic growth trend models such as Equation 7.3 are appropriate

for the tree-ring data being analyzed, a theoretical basis for their use can be claimed, which may make any identified pollution effects more tenable.

In closed-canopy forests, the effects of between-tree competition and disturbances can cause an observed trend in ring widths to depart significantly from that predicted by theoretical growth models such as Equation 7.3 (Cook 1987a, b). When this is the case, the expectation of decreasing ring width with increasing age is often inappropriate. This condition complicates the search for D2 because now the effects of both A and D1 have to be taken into account before the existence of D2 can be tested. The simultaneous estimation of A and D1 using flexible curve fitting and smoothing methods, such as orthogonal polynomials (Fritts 1976) and smoothing splines (Cook and Peters 1981), cannot differentiate between D1 and D2. Consequently, there is some danger that the pollution signal of interest will be inadvertently removed as part of the joint estimation of A and D1. However, there are ways of reducing the impact of D1 without directly estimating it by exploiting the spatial randomness of endogenous disturbances as they affect trees in a stand (Cook 1985).

Component C in Equation 7.2 represents the integrated effect of climatically-related environmental variables on tree growth, except those that are only associated with stand disturbances. Typical variables composing C are precipitation, temperature, and heat sums as they affect available moisture supply, evapotranspiration demand, phenology, and rates of reactions. These variables are assumed to affect all trees in a stand similarly. Thus, C is a signal in common to the sampled trees and is usually the principal source of marker years used for cross-dating tree rings. Some climatic variables that have been used to model C are monthly temperature and precipitation (Fritts 1976), and drought indices (Cook and Jacoby 1977). These variables are usually regarded as stationary stochastic processes although they may be persistent in an autoregressive sense (Gilman et al. 1963) and can possess trend (e.g., Jones et al. 1986, Bradley et al. 1987).

When possible, the influence of climate on ring width should be modeled as part of any study of pollution effects on forests (Cook 1987a). An unusual reduction in ring width that appears consistent with hypothesized pollution effects could, in fact, be caused by adverse climatic extremes or climatic change. If this were the case, then a pollution hypothesis could be falsely accepted. Alternately, it is possible that better-than-average climatic conditions might compensate for an air pollution effect and largely mask a growth reduction due to airborne chemicals. If this were the case, then a pollution hypothesis could be falsely rejected.

Puckett (1982) proposed that a change in the climatic response of trees may be an indicator of physiological dysfunction caused by air pollution; this change could occur even in the absence of an abnormal ring-width reduction. Therefore, it offers the possibility of a different kind of tree-ring indicator of pollution stress in trees. The physiological basis for expecting a change in climatic response from exposure to air pollutants has not yet been established, so time-dependence in any statistical properties of tree rings is not necessarily strong evidence for a pollution effect on tree growth. The statistical techniques for seeking such changes in tree rings are available (e.g., Visser and Molenaar 1986, 1988, Cook et al. 1987, Van Deusen 1987, 1989, 1990) and can be readily applied in ways that may yield some evidence of air pollution effects.

As specified in Equation 7.2, D1 or D2 are present in the ring widths only after some arrival time t0 and usually decay to zero (effectively) given sufficient time. This intervention model for disturbance signals in tree rings is appropriate if the physical or biological mechanisms of disturbance can be modeled as impulses or spikes that shock a tree's physiology at time t0 and than disappear. For example, the formation of a gap by treefall in a closed-canopy forest occurs instantaneously, a ground fire may pass through a stand in a matter of minutes to hours, and insect defoliation may only occur over one growing season. Because these disturbances are confined to one growing season (i.e. the sampling interval of tree rings), they can be modeled as spikes having the general form [... 0 0 1 0 0 ...] with the sign of the spike being dependent on the effect of the disturbance on growth.

The general spike intervention model for disturbances proposed above is not appropriate if the intervention causes a long-term or permanent change of state in the forest environment. The hypothesized effect of airborne chemicals on forest ecosystems fits into this latter kind of intervention model because anthropogenic emissions of ozone precursors, ammonium, nitrogen oxides, and sulfur dioxide have been continuously added to the environment throughout the past century (Husar 1989) and especially since 1940 in certain parts of the United States. Consequently, if D2 is present in tree rings and is caused by air pollution, its form is not likely to be that of a pulse. Rather, it may be more like a step having the general form [...0 0 1 1 1...] or even a ramp. Of course, a tree's response to a step intervention is unlikely to look like a pure step because of physiological persistence, delays in response, and the possible masking effects of other variables such as climate and endogenous disturbances. However, if persistence, delays, and masking are taken into account when modeling interventions, it is possible to recover the form of the original intervention to a reasonable approximation. Box and Tiao (1975) provide details on the characterization of interventions in time series.

E represents the unexplained variance in the ring-width series after the contributions of A, C, D1, and D2 have been taken into account. Some possible sources of E are microsite variations within the stand, gradients in soil chemistry and hydrology, genetic variability within the sampled population, and measurement error. E is assumed to be serially uncorrelated within and spatially uncorrelated between trees in the stand, although the latter assumption may be difficult to satisfy without explicitly modeling the spatial autocorrelation of the errors. In fact, the difficulty in satisfying this ideal error structure using traditional dendrochronological methods has lead to new and innovative techniques of simultaneous estimation that allow for much more general error structures (Eriksson 1989, Van Deusen 1989).

Methods of Detecting Change in Tree-Ring Series

The conceptual model just described emphasized the notion that a pollution effect on tree growth should be viewed as an exogenous disturbance or an intervention of a new kind of stress into the forest ecosystem. The jargon of intervention analysis (sensu Box and Tiao 1975) has also been used as a convenient way of introducing this topic. However, there are different ways of searching for the presence of an intervention in tree rings that may be due to pollution stress, and we do not necessarily advocate any particular method of analysis for this purpose. Indeed, the variety of statistical methods used in this book to analyze tree-ring data for possible pollution effects illustrates the rich variety of approaches one may take in such studies.

Consider now a suite of m cross-dated and measured ring-width series from a stand of trees that is hypothesized to be impacted by airborne chemicals. On the premise that this impact should be revealed by some anomalous property in the tree rings, what statistical methods might be applied to test this intervention?

A frequently applied approach, which is based on the experience of dendroclimatologists in modeling climatic signals in tree rings, has been to detrend and standardize (sensu Fritts 1976) each ring-width series and then average the standardized tree-ring indices into a mean-value function. This is accomplished by independently fitting a growth curve to each ring-width series as an estimate of A, and perhaps D1. The tree-ring indices are then calculated as

$$I = R / G \qquad \text{(Equation 7.4)}$$

where:

I is the series of dimensionless tree-ring indices having a defined mean of 1.0 and homoscedastic variance,

R is the measured ring-width series, and

G is a growth curve equal to A+dD1.

Of course, if d=0 or G is constrained to a simple deterministic family of growth curves (e.g., Fritts et al. 1969), G reduces to A. Otherwise, more flexible growth curves (e.g., Cook and Peters 1981) might be used that jointly estimate A+D1. Note that Equation 7.4 is still compatible with the linear aggregate model proposed earlier because the logarithmic transformation of R would linearize the operation of computing tree-ring indices.

Assume for now that d=0 for D1. Then, the tree-ring indices computed by Equation 7.4 are expressed as:

$$I = C + dD2 + E \qquad \text{(Equation 7.5)}$$

Assuming that C and D2 are common to all trees and the error variance E is serially and spatially uncorrelated within and between trees, the mean-value function of tree-ring indices will reduce E as a function of $1/n$ and produce better estimates of C and D2 than exist in any one series of indices. This should enhance the probability of finding a pollution signal, should it exist, providing that the estimation of G has not inadvertently removed it from the tree rings. Now if d=1 for D1 and G=A, then

$$I = C + D1 + dD2 + E \qquad \text{(Equation 7.6)}$$

This potentially complicates the search for D2 because, as described earlier, there may not be any way of differentiating D1 from D2 in individual tree-ring series. But given that the arrival time of D1 is assumed uncorrelated between trees not adjacent to the same gap, the variance accounted for by D1 can also be reduced in the mean-value function by averaging. The mean-value function can then be tested for anomalous residual negative growth departures and time-dependent climatic effects that may be indicative of pollution stress.

Mean-value functions of tree-ring indices have been used in various ways to study the impact of air pollution on tree growth. In studies where tree-ring sites were situated along well defined pollution gradients produced by intense point-sources such as copper smelters, changes in some attributes of mean tree growth have been correlated with the known gradients (e.g., Nash et al. 1975, Thompson 1981, McClenahen and Dochinger 1985, Fox et al. 1986). These changes included anomalous reductions in growth and a change in the ability of climate to predict tree-ring indices as the sites approached the pollution point-sources. Kincaid (1987) was even able to quantify growth loss as a function of changing sulfur dioxide emissions.

In other studies where air pollution is regional and the exposures of forests lower, the analyses have been more difficult and the interpretations more tenuous. Puckett (1982) used response function analysis (sensu Fritts 1976) to search for changes in climatic response, which could indicate a response to acid rain, by splitting the data into two equal time periods and comparing the fitted climate models. Although he found apparent evidence for a change in response between the two periods that he interpreted as evidence for anomalous behavior, the results were questionable because of uncertainties about the small sample stability of response functions.

As a means of reducing this uncertainty, Cook (1987a) devised a multiple linear regression method that uses forecasts or extrapolations of tree rings from a fitted climate model to test for changes in the predictive ability of tree rings by climate. A critical provision of this method was the use of a validation period for testing the stability of the climatic response model (i.e. the correctness of the selected climate variables) before it was used to extrapolate into the time period when the trees were suspected of being affected by some new stress like air pollution. This method was used to study the decline of red spruce (*Picea rubens* Sarg.) in the Appalachian Mountains of the eastern United States. In analyzing 35 mean index chronologies of red spruce, the validated climatic response models were not able to predict the standardized tree-ring indices after 1960, either in mean level (McLaughlin et al. 1987) or in changes from year-to-year (Johnson et al. 1988). These results suggested that a change had occurred in the environment of red spruce that was coincidental with the beginning of its documented decline.

About the same time, Visser and Molenaar (1986, 1988) and Van Deusen (1987, 1989, 1990) independently applied the Kalman filter (Harvey 1984) to the problem of estimating time-dependent or dynamic regression models in tree-ring analysis. Presently, this is the most powerful method available for that purpose because its mathematical theory is well developed and it does not require a priori information about the timing of pollution effects, as Cook's (1987a) method does. When Visser and Molenaar (1986) used the Kalman filter to reanalyze the same data used by Puckett (1982), they found that there was little evidence for time-dependence of the kind previously claimed. This result probably reflects the poor stability of the response function method for small sample sizes by Puckett (1982). Since then, Cook and Johnson (1989) have shown with the Kalman filter that there is an elevational dependence in the response of red spruce to summer and winter temperatures and that the change in climatic response in red spruce after 1960 may not have been as abrupt as previously thought. In addition, their results suggest that red spruce has been responding to changing climate and new climatic variables since the 1920s. These new insights would have been difficult to obtain

without the Kalman filter, which is rapidly becoming the standard method of analysis for testing the presence of time-dependence in tree rings.

The use of mean-value functions is appealing on statistical grounds. The estimation of C and the search for D2 is made presumably easier by reducing the noise variance in the data due to E and D1 by ~1/m, and by reducing the dimensions of the problem from m to only one series. However, the use of averaged tree-ring data can be criticized for losing too much individual tree information. Using a tree-ring mean-value function relies on an implied assumption that the tree-ring series being averaged belong to the same population in terms of climatic response and genetic sensitivity to air pollution. To the extent that cross-dating implies a common environmental signal between trees that is often related to climate, it would seem that averaging is appropriate when cross-dating is strong. However, there may be tree-ring sites of interest where the trees cross-date weakly, suggesting considerable heterogeneity in climatic response between trees. In this case, it might be useful to model individual tree-ring series for climate and pollution effects. The use of individual radial increment series in this kind of study is comparatively new and could add substantial new information to our understanding of how individual trees and forests respond to environmental stress. However, it must also be recognized that the noise level in individual radial increment series is likely to be very high due to the unattenuated contributions of D1 and E, thus making the problem of differentiating D2 from D1 more formidable and generally less certain.

Genetic variation in ring widths could derive from either normal variations in growth within a gene pool, or from greater sensitivity of some genotypes to pollutants. An independent means of separating the trees into sensitivity classes (such as foliar symptoms; Peterson et al. 1987 and Chapter 11) is needed to distinguish between these two possibilities.

The sequential analysis of tree rings, where each stage of analysis is independent of all other stages (e.g., first detrend, then average, and finally regress), has been criticized by Van Deusen (1989) and Eriksson (1989) for not properly handling the error structure and aggregation of tree-ring series implied by the linear aggregate model. For example, Van Deusen (1989) noted that prewhitening tree rings before doing the regressions on climate, as done by Cook et al. (1987) and in Chapter 8 of this volume, is not appropriate because autocorrelation in the tree rings should be handled as part of the error structure of the model, not removed prior to regression. It is not clear that this theoretically valid criticism has any serious consequences in practice. For example, the

climate model for red spruce appears to be robust with respect to the tree-ring and climate data being analyzed, the method of analysis, and the analyst (e.g., Cook et al. 1987, Federer et al. 1989, Van Deusen 1990).

Van Deusen (1989) and Eriksson (1989) also noted that detrending, climate modeling, and the search for time-dependent effects should all be done simultaneously across the full suite of tree-ring series from a stand. Van Deusen (1989) describes an exponential aggregate model for this purpose, and Eriksson (1989) proposes a random coefficient model specifically designed for analyzing longitudinal data (of which tree rings are a form). Each method requires some rather simple assumptions about the form of the growth trend model, and the full random coefficient model requires the estimation of a very large number of parameters. Neither method has been used enough on tree-ring data to tell if any significant benefits will arise from these more complicated approaches.

An alternative method for detecting changes in tree-ring series, either in individual records or in mean-value functions, is intervention detection (Downing and McLaughlin 1987). This method basically uses the time series outlier detection method of Chang (1982) coupled with autoregressive-moving average (ARMA) time series modeling (Box and Jenkins 1976) and intervention analysis (Box and Tiao 1975) to exhaustively search for unusual pulses or step-like changes in time series residuals. To date, the only application of intervention detection to the study of forest decline is that of McLaughlin et al. (1987) and Downing and McLaughlin (1987), who analyzed 2,433 red spruce tree-ring series for statistical evidence of anomalous ring-width declines. They found that the frequency of identified negative-step interventions peaked in the 1955-59 period, which generally agreed with previous estimates of when red spruce began to decline in the northern Appalachian Mountains (e.g., Johnson and McLaughlin 1986).

Conclusions

The methods of analysis described here provide an introduction to some of the approaches and methods used in the tree-ring studies described in this book (Table 7.4). It is clear that no consensus exists on how to statistically analyze tree rings, which is both a blessing and a curse. The paucity of useful biological theory for guiding tree-ring analyses through the thicket of available statistical methodologies means that there will always be justifiable concerns about the meaning of statistical associations and the validity of causal inferences drawn from them. This is especially true in the often controversial study of air pollution and its

effect on tree growth. However, the fact that different data analysts and statisticians may analyze the same data in quite different ways, means that there is room for innovation, improvements in methods, and independent validation of results. Thus, tree-ring analyses can be very robust and provide new insights into how trees interact with their environment.

Table 7.4 General tree-ring analysis approaches and methods used in Chapters 8–11 of this book. A ● means that the tree-ring analyses in the chapter explicitly examined the tree-ring data for certain classes of variance described in this section. See the specific chapters for details of the statistical methods used.

	Chapter 8	Chapter 9 A	Chapter 9 B	Chapter 10	Chapter 11
Growth-trend estimation and analysis	●	●		●	
Single tree-ring index chronology	●		●		●
Mean tree-ring index chronology analysis	●	●	●	●	
Climatic response modeling	●	●	●	●	
Endogenous disturbance analysis	●				
Exogenous disturbance analysis: Climate model extrapolation tests	●	●		●	
Exogenous disturbance analysis: Time-dependent models using the Kalman filter			●		●

References

Aitken WM, Jacobi WR, Staley JM (1984) Ozone effects on seedlings of Rocky Mountain ponderosa pine. *Plant Disease* 68:398–401

Allison JR (1984) *An Evaluation of Ozone Injury to Pines on the Tahoe National Forest*. Forest Pest Management, Pacific Southwest Region, Report No. 84–30

Arbaugh M, Bednar L, Moore J, Cline S (1991) Statistical recommendations for index construction, plot design, and data gathering methods to monitor long-term effects of ozone on conifer forests of the Sierra Nevada. In: Stolte KW, Miller PR (eds) *Management Recommendations and Specifications for Plot Design and Sampling Methods to Monitor Long-term Effects of Ozone on Western Coniferous Forests*. Proceedings of a Pine Plot Workshop. March 14–15, 1989, Riverside, California. US Forest Service, Southeastern Forest Experiment Station, Research Triangle Park, NC, 88p

Axelrod MC, Coyne PI, Bingham GE, Kircher JR, Miller PR, Hung RC (1980) Canopy analysis of pollutant injured ponderosa pine in the San Bernardino National Forest. In: *Proceedings of the Symposium on Effects of Air Pollutants on Mediterranean and Temperate Forest Ecosystems*. USDA Forest Service General Technical Report PSW-43

Baes CF, McLaughlin SB (1984) Trace elements in tree rings: Evidence of recent and historical air pollution. *Science* 224:494–497

Barrett TW, Benedict HM (1970) Sulfur Dioxide. In: Jacobson JS, Hill AC (eds) *Recognition of Air Pollution Injury to Vegetation: A Pictorial Atlas*. Air Pollution Control Association, Pittsburgh

Box GEP, Tiao GC (1975) Intervention analysis with applications to environmental and economic problems. *Journal of the American Statistical Association* 70:70–79

Box GEP, Jenkins GM (1976) *Time Series Analysis: Forecasting and Control*. Holden-Day, San Francisco

Box GEP, Hunter WG, Hunter JS (1978) *Statistics for Experimenters*. John Wiley & Sons, New York, 653p

Bradley RS, Diaz HF, Eischeid JK, Jones PD, Kelly PM, Goodess CM (1987) Precipitation fluctuations over Northern Hemisphere land areas since the mid-19th century. *Science* 237:171–175

Bunce HWF (1979) Fluoride emissions and forest growth. *Journal of the Air Pollution Control Association* 29:642–643

Bunce HWF (1984) Fluoride emissions and forest survival, growth and regeneration. *Environmental Pollution (Series A)* 35:169–188

Carlson CE (1974) *Sulfur Damage to Douglas-fir Near a Pulp and Paper Mill in Western Montana.* USDA Forest Service, Division State and Private Forestry Publication Number 74-13

Carlson CE, Dewey JE (1972) *Environmental Pollution by Fluorides in Flathead National Forest and Glacier National Park.* US Department of Agriculture Forest Service, Northern Region Headquarters, Forest Insect and Disease Branch, Missoula

Carlson CE, Hammer WP (1975) Impact of fluorides and insects on radial growth of lodgepole pine near an aluminum smelter in northwestern Montana. Abstract from: *Proceedings of the Montana Academy of Sciences* 35:9

Chang I (1982) *Outliers in Time Series.* PhD dissertation. University of Wisconsin, Madison

Cline SP, Burkman WG (1989) The role of quality assurance in ecological research programs. In: Bucher JB, Bucher-Wallin I (eds) *Air Pollution and Forest Decline: Proceedings of the 14th International Meeting for Specialists in Air Pollution Effects on Forest Ecosystems.* IUFRO P2.05, Interlaken, Switzerland, 2–8 October, 1988, Birmensdorf, 1989, pp 361–365

Cline SP, Burkman WG, Geron CD (1989) Use of quality control procedures to assess errors in measuring forest canopy condition. In: Olson RK, Lefohn AS (eds) *Effects of Air Pollution on Western Forests.* Transactions Series, No. 16, Air and Waste Management Association, Pittsburgh, pp 379–387

Conkey LE (1988) Decline in old-growth red spruce in western Maine: An analysis of wood density and climate. *Canadian Journal of Forestry Research* 18:1063–1068

Cook ER (1985) *A Time Series Analysis Approach to Tree-Ring Standardization.* PhD dissertation. University of Arizona, Tucson

Cook ER (1987a) The use and limitations of dendrochronology in studying effects of air pollution on forests. In: Hutchinson TC, Meema KM (eds) *Effects of Atmospheric Pollutants on Forests, Wetlands, and Agricultural Ecosystems.* Springer-Verlag, Berlin, pp 277–290

Cook ER (1987b) The decomposition of tree-ring series for environmental studies. *Tree-Ring Bulletin* 47:37–59

Cook ER, Johnson AH, Blasing TJ (1987) Forest decline: Modeling the effect of climate in tree rings. *Tree Physiology* 3:27–40

Cook ER, Innes J (1989) Tree-ring analysis as an aid to evaluating the effects of air pollution on tree growth. In: Woodwell GM (chairman) *Biologic Markers of Air-Pollution Stress and Damage in Forests.* National Academy Press, Washington, DC, pp 157–168

Cook ER, Jacoby GC (1977) Tree-ring-drought relationships in the Hudson Valley, New York. *Science* 198:399–401

Cook ER, Kairiukstis LA (eds) (1990) *Methods of Dendrochronology: Applications in the Environmental Sciences.* Kluwer Academic Publishers, Dordrecht

Cook ER, Peters K (1981) The smoothing spline: A new approach to standardizing forest interior tree-ring width series for dendroclimatic studies. *Tree-Ring Bulletin* 41:45–53

Cook ER, Johnson AH (1989) Climate change and forest decline: A review of the red spruce case. *Water, Air and Soil Pollution* 48:127–140

Coyne PI, Bingham GE (1981) Comparative ozone dose response of gas exchange in a ponderosa pine stand exposed to long-term fumigations. *Journal of the Air Pollution Control Association* 31:38–41

Coyne PI, Bingham GE (1982) Variation in photosynthesis and stomatal conductance in an ozone-stressed ponderosa pine stand: Light response. *Forest Science* 28:27

Davis DD, Wilhour RG (1976) *Susceptibility of Woody Plants to Sulfur Dioxide and Photochemical Oxidants.* EPA Ecological Research Series, EPA-600/3-76-102

Downing D, McLaughlin SB (1987) Intervention detection—a systematic technique for examining shifts in radial growth rates of forest trees. In: Jacoby GC, Hornbeck JW (eds) *Proceedings of the International Symposium on Ecological Aspects of Tree-Ring Analysis.* United States Department of Energy, Washington, DC pp 543–554

Duriscoe DM (1987a) *Evaluation of Ozone Injury to Selected Tree Species in the Rincon Mountains of Arizona, 1985 Survey Results.* A report by Holcomb Research Institute, Butler University. USDI National Park Service, Air Quality Division, Denver, CO, 138p

Duriscoe DM (1987b) *Evaluation of Ozone Injury to Selected Tree Species in Sequoia and Kings Canyon National Parks, 1985 Survey Results.* A report by Holcomb Research Institute, Butler University. USDI National Park Service, Air Quality Division, Denver, CO, 228p

Duriscoe DM (1990) *Evaluation of Ozone Injury to Selected Tree Species in Sequoia and Kings Canyon National Parks, 1986 Survey Results.* Holcomb Research Institute, Butler University, Indianapolis

Duriscoe DM (1991) *Methods for Sampling of Pinus ponderosa and Pinus jeffreyi for the Evaluation of Oxidant-induced Foliar Injury,* Final Report Contract #CX-0001-4-0058, Work Assignment #14, submitted to USDI National Park Service, Air Quality Division, Denver, CO

Duriscoe DM, Stitt SCF (1990) *Sampling Design and Sample Acquisition for Elemental Baseline Study in North Cascades National Park Complex.* Final Report Contract #CX-0001-4-0058, Work Assignment #24, submitted to USDI National Park Service, Air Quality Division, Denver, CO

Duriscoe DM, Stolte KW (1989) Photochemical oxidant injury to ponderosa pine (*Pinus ponderosa* Laws.) and Jeffrey pine (*Pinus jeffreyi* Grev. and Balf.) in the national parks of the Sierra Nevada of California. In: Olson RK, Lefohn AS (eds) *Effects of Air Pollution on Western Forests.* Transactions Series, No. 16, Air and Waste Management Association, Pittsburgh, pp 261–278

Eriksson M (1989) *Integrating Forest Growth and Dendrochronological Methodologies.* PhD dissertation, University of Minnesota, St. Paul

Evans LS, Miller PR (1972a) Ozone damage to ponderosa pine: A histological and histochemical appraisal. *American Journal of Botany* 59:297–304

Evans LS, Miller PR (1972b) Comparative needle anatomy and relative ozone sensitivity of four pine species. *Canadian Journal of Botany* 50:1067–1071

Ewell DM, Mazzu LC, Duriscoe DM (1989) Specific leaf weight and other characteristics of ponderosa pine as related to visible ozone injury. In: Olson RK, Lefohn AS (eds) *Effects of Air Pollution on Western Forests.* Transactions Series, No. 16, Air and Waste Management Association, Pittsburgh, pp 411–418

Ewers FW, Schmidt R (1982) Longevity of needle fascicles of *Pinus longaeva* and other north American pines. *Oecologia* 51:107–115

Federer CA, Triton LM, Hornbeck JW, Smith RB (1989) Physiologically based dendroclimate models for effects of weather on red spruce basal-area growth. *Agricultural and Forest Meteorology* 46:159–172

Fox CA, Kincaid WB, Nash TH, Young DL, Fritts HC (1986) Tree-ring variation in western larch (*Larix occidentalis*) exposed to sulfur dioxide emissions. *Canadian Journal of Forest Research* 16:283–292

Fritts HC (1976) *Tree Rings and Climate.* Academic Press, London

Fritts HC, Mosimann JE, Bottorff CP (1969) A revised computer program for standardizing tree-ring series. *Tree-Ring Bulletin* 29:15–20

Gilman DL, Fuglister FJ, Mitchell JM (1963) On the power spectrum of "red noise." *Journal of the Atmospheric Sciences* 20:182–184

Gordon CC (1974) *Environmental Effects of Fluoride: Glacier National Park and Vicinity, 1974.* Final Report to the US Environmental Protection Agency—Region VIII. EPA-908/1-74-001

Grulke NE, Miller PR, Wilborn RD, Hahn S (1989) Photosynthetic response of giant sequoia seedlings and rooted branchlets of mature foliage to ozone fumigation. In: Olson RK, Lefohn AS (eds) *Effects of Air Pollution on Western Forests.* Transactions Series, No. 16, Air and Waste Management Association, Pittsburgh, pp 429–441

Gumpertz ML, Tingey DT, Hogsett WE (1982) Precision and accuracy of visual foliar injury assessments. *Journal of Environmental Quality* 11:549–553

Haggett P, Cliff AD, Frey A (1977) *Locational Methods.* Edward Arnold, London

Harvey AC (1984) A unified view of statistical forecasting procedures. *Journal of Forecasting* 3:245–275

Heck WW, Dunning JA, Hindawi CJ (1965) Interactions of environmental factors on the sensitivity of plants to air pollution. *Journal of the Air Pollution Control Association* 15: 511–515

Hill AC Heggestad HE, Linzon SN (1970) Ozone. In: Jacobson JS, Hill AC (eds) *Recognition of Air Pollution Injury to Vegetation: A Pictorial Atlas.* Air Pollution Control Association, Pittsburgh, pp B1–B22

Hornbeck JW, Smith RB (1985) Documentation of red spruce growth decline. *Canadian Journal of Forest Research* 15:1199–1201

Horsfall JG, Barratt RW (1945) An improved grading system for measuring plant disease. *Phytopathology* 35:655

Horsfall JG, Cowling EB (1978) Pathometry: The measurement of plant disease. In: *Plant Disease: An Advanced Treatise. Vol. 2: How Disease Develops in Populations.* Academic Press, New York, pp 119–136

Hughes MK, Kelly PM, Pilcher JR, LaMarche JR (eds) (1982) *Climate from Tree Rings*. Cambridge University Press, Cambridge

Husar RB (1989) Air pollutant distribution and trends. In: Woodwell GM (chairman), *Biologic Markers of Air-Pollution Stress and Damage in Forests*. National Academy Press, Washington, DC, pp 29–46

Hutchinson TC, Whitby LM (1976) The effects of acid rainfall and heavy metal particulates on a boreal forest ecosystem near the Sudbury smelting region of Canada. In: Dochinger LS, Seliga TA (eds) *Proceedings of the First International Symposium on Acidic Precipitation and the Forest Ecosystem*. USDA Forest Service General Technical Report No. NE-23, Upper Darby, PA, pp 745–765

Huttunen S (1984) Interactions of disease and other stress factors with atmospheric pollution. In: Treshow M (ed) *Air Pollution and Plant Life*. Wiley, Chichester, pp 321–356

Hyink DM, Zedacker SM (1987) Stand dynamics and the evaluation of forest decline. *Tree Physiology* 3:17–26

Innis JL (1988) Forest health surveys: A critique. *Environmental Pollution* 54:1–15

Jackson LL, Gough LP (1989) The use of stable sulfur isotope ratios in air pollution studies: An ecosystem approach in south Florida. In: Rundel PW, Ehleringer JR, Nagey KA (eds) *Stable Isotopes in Ecological Research, Ecological Studies Volume 68*. Springer-Verlag, New York, pp 471–490

Jacobson JS, Hill AC (1970) *Recognition of Air Pollution Injury to Vegetation: A Pictorial Atlas*. Air Pollution Control Association, Pittsburgh

James RL, Staley JM (1980) *Photochemical Air Pollution Damage Survey of Ponderosa Pine Within and Adjacent to Denver, Colorado: A Preliminary Report*. USDA Forest Service Forest Insect and Disease Management, Biological Evaluation R2-80-6

Johnson AH, Cook ER, Siccama TG (1988) Climate and red spruce growth and decline in the northern Appalachians. *Proceedings of the National Academy of Sciences* 85:5369–5373

Johnson AH, McLaughlin SB (1986) The nature and timing of the deterioration of red spruce in the northern Appalachian Mountains. In: *National Research Council, Acid Deposition Long-Term Trends*. National Academy Press, Washington, DC, pp 200–230

Jones PD, Raper SCB, Bradley RS, Diaz HF, Kelly PM, Wigley TML (1986) Northern hemisphere surface air temperature variations, 1851–1984. *Journal of Climate and Applied Meteorology* 25:161–179

Kincaid WB (1987) Dendrochronological analysis of ambient sulfur dioxide effects in western larch. In: Jacoby GC, Hornbeck JW (eds) *Proceedings of the International Symposium on Ecological Aspects of Tree-Ring Analysis*. United States Department of Energy, Washington, DC, pp 410–416

Krouse HR (1974) Sulphur isotope abundance elucidates uptake of atmospheric sulphur emissions by vegetation. *Nature* 265:45–46

Larsh RN, Miller PR, Wert SL (1970) Aerial photography to detect and evalute air pollution damaged ponderosa pine. *Journal of the Air Pollution Control Association* 20:289–292

LeBlanc DC, Raynal DJ, White EH (1987a) Acidic deposition and tree growth: I. The use of stem analysis to study historical growth patterns. *Journal of Environmental Quality* 16:325–333

LeBlanc DC, Raynal DJ, White EH (1987b) Acidic deposition and tree growth: II. Assessing the role of climate in recent growth declines. *Journal of Environmental Quality* 16:334–340

Lepp NW (ed) (1981a) *Effect of Heavy Metal Pollution on Plants. Volume 1. Effects of Trace Metals on Plant Function*. Pollution Monitoring Series, Applied Science Publishers

Lepp NW (ed) (1981b) *Effect of Heavy Metal Pollution on Plants. Volume 2. Metals in the Environment*. Pollution Monitoring Series, Applied Science Publishers

MacKenzie JJ, El-Ashry MT (eds) (1989) *Air Pollution's Toll on Forests and Crops*. Yale University Press, New Haven

McClenahen JR, Dochinger LS (1985) Tree ring response of white oak to climate and air pollution near the Ohio River Valley. *Journal of Environmental Quality* 14:274–280

McLaughlin SB, Downing DJ, Blasing TJ, Cook ER, Adams HS (1987) An analysis of climate and competition as contributors to decline of red spruce in high elevation Appalachian forests of the eastern United States. *Oecologia* 72:487–501

Miller PR (1973) Oxidant-induced community change in a mixed conifer forest. In: Naegele JA (eds) *Air Pollution Damage to Vegetation*. American Chemical Society, Washington, DC, pp 101–117

Miller PR (ed) (1977) *Photochemical Oxidant Air Pollutant Effects on a Mixed Conifer Forest Ecosystem*. Annual Progress Report, 1975–1976, EPA-600/3-77-104, US Environmental Protection Agency

Miller PR (1989) Biomarkers for defining air pollution effects in Western coniferous forests. In: Woodwell GM (chairman) *Biologic Markers of Air Pollution Stress and Damage in Forests*. National Academy Press, Washington, DC, pp 111–118

Miller PR, Evans LS (1974) Histopathology of oxidant injury and winter fleck injury on needles of western pines. *Phytopathology* 64:801–806

Miller PR, Millecan AA (1971) Extent of oxidant air pollution damage to some pines and other conifers in California. *Plant Disease Reporter* 55:555–559

Miller PR, Van Doren RE (1982) Ponderosa and Jeffrey pine foliage retention indicates ozone dose response. In: Conrad CE, Oechel WC (eds) *Proceedings of the Symposium on Dynamics and Management of Mediterranean-type Ecosystems*. USDA Forest Service General Technical Report PSW-58, Berkeley, CA

Miller PR, Parmeter JR Jr, Taylor OC, Cardiff EA (1963) Ozone injury to the foliage of *Pinus ponderosa*. *Phytopathology* 53:1072–1076

Miller PR, Taylor OC, Wilhour RG (1982) *Oxidant Air Pollution Effects on a Western Coniferous Forest Ecosystem*. Environmental Protection Agency, Environmental Research Brief EPA-600/D-82-276

Miller PR, Longbotham GJ, Longbotham CR (1983) Sensitivity of selected western conifers to ozone. *Plant Disease* 67:1113–1115

Miller PR, McBride JR, Schilling SL, Gomez AP (1989) Trend of ozone damage to conifer forests between 1974 and 1988 in the San Bernardino Mountains of southern California. In: Olson RK, Lefohn AS (eds) *Effects of Air Pollution on Western Forests*. Transactions Series, No. 16, Air and Waste Management Association, Pittsburgh, pp 309–324

Muir PS, Armentano TV (1987) *Evaluating Oxidant-induced Injury to Foliage of Pinus ponderosa (west) and Pinus strobus (east): A Comparison of Methods*. Interim Report to the US National Park Service, Air Quality Division, Holcomb Research Institute, Butler University, Indianapolis

Muir PS, McCune B (1987) Index construction for foliar symptoms of air pollution injury. *Plant Disease* 71(6): 558–565

Munz PA, Keck DD (1973) *A California Flora*. University of California Press

Nash TH, Fritts HC, Stokes MA (1975) A technique for examining non-climatic variation in widths of tree rings with special reference to air pollution. *Tree-Ring Bulletin* 35:15–24

National Research Council (1989) *Biologic Markers of Air-Pollution Stress and Damage in Forests*. National Academy Press, Washington, DC

National Research Council of Canada (1939) *Effect of Sulphur Dioxide on Vegetation*. The Associate Committee on Trail Smelter Smoke, Ottawa, Canada, N.R.C. No. 815

Nriagu JO (ed) (1978) *Sulfur in the Environment. Part II: Ecological Impacts*. Wiley, New York

Parmeter JR, Miller PR (1968) Studies relating to the cause of decline and death of ponderosa pine in southern California. *Plant Disease Reporter* 52:707–711

Parmeter JR, Bega RV, Neff T (1962) A chlorotic decline of ponderosa pine in southern California. *Plant Disease Reporter* 46: 269–273

Patterson MT (1991) Physiological responses of Jeffrey pines to ozone in Sequoia National Park. In: Stolte KW, Miller PR (eds) *Management Recommendations and Specifications for Plot Design and Sampling Methods to Monitor Long-term Effects of Ozone on Western Coniferous Forests*. Proceedings of a Pine Plot Workshop, March 14–15, 1989, Riverside, California. US Forest Service, Southeastern Forest Experiment Station, Research Triangle Park, NC, 88p

Patterson MT, Rundel PW (1989) Seasonal physiological responses of ozone stressed jeffrey pine in Sequoia National Park, California. In: Olson RK, Lefohn AS (eds) *Effects of Air Pollution on Western Forests*. Transactions Series, No. 16, Air and Waste Management Association, Pittsburgh, pp 419–428

Peterson DL, Arbaugh MJ, Wakefield VA, Miller PR (1987) Evidence of growth reduction in ozone-injured Jeffrey pine (*Pinus jeffreyi* Grev. and Balf.) in Sequoia and Kings Canyon National Parks. *Journal of the Air Pollution Control Association* 37:906–912

Peterson DL, Arbaugh MJ, Robinson LJ (1989) Ozone injury and growth trends of ponderosa pine in the Sierra Nevada. In: Olson RK, Lefohn AS (eds) *Effects of Air Pollution on Western Forests*, Transactions Series, No. 16, Air and Waste Management Association, Pittsburgh, pp 293–307

Phipps RL, Whiton JC (1988) Decline in long-term growth trends of white oak. *Canadian Journal of Forest Research* 18:24–32

Pronos J, Vogler DR, Smith RS (1978) *An Evaluation of Ozone Injury to Pines in the Southern Sierra Nevada*. USDA Forest Service, Pacific Southwest Region, Forest Pest Management Report No. 78-1

Puckett LJ (1982) Acid rain, air pollution, and tree growth in southeastern New York. *Journal of Environmental Quality* 11:376–381

Pye JM (1988) Impact of ozone on the growth and yield of trees: A review. *Journal of Environmental Quality* 17:347–360

Rice PM, Boldi RA, Carlson CE, Tourangeau PC, Gordon CC (1983) Sensitivity of *Pinus ponderosa* foliage to airborne phytotoxins: Use in biomonitoring. *Canadian Journal of Forest Research* 13:1083–1091

Richards BL, Taylor OC, Edmunds GF (1968) Ozone needle mottle of pine in southern California. *Journal of the Air Pollution Control Association* 18:73–77

Rock BN, Vogelmann JE, Williams DL, Vogelmann AF, Hoshizaki T (1986) Remote detection of forest damage. *BioScience* 36:439–445

Rock BN, Hoshizaki T, Miller JR (1988) Comparison of in situ and airborne spectral measurements of the blue shift associated with forest decline. *Remote Sensing of Environment* 24:109–127

Rock BN, Vogelmann JE, Defeo NF (1989) The use of remote sensing for the study of air pollution effects in forests. In: Woodwell GM (chairman) *Biologic Markers of Air-Pollution Stress and Damage in Forests*. National Academy Press, Washington, DC, pp 183–194

Scholz FH, Gregorius R, Rudin D (1989) Genetic effects of air pollutants in forest tree populations. *Proceedings of the Joint Meeting of the IUFRO Working Parties in Grobhansdorf*. August 3–7, 1987

Schweingruber FH (1986) Abrupt growth changes in conifers. *IAWA Bulletin* 7:277–283

Severson RC, Crock JG, Gough LP (1990) *An Assessment of the Geochemical Variability for Plants and Soils and an Evaluation of Industrial Emissions near the Kenai National Wildlife Refuge, Alaska*. US Geological Survery Open File Report 90-306

Smith WH (1990) *Air Pollution and Forests*. Springer-Verlag, New York

Snedecor GW, Cochran WG (1967) *Statistical Methods, 7th edition*. Iowa State University Press, 50p

Solberg RA, Adams DF, Ferchau HA (1957) Some effects of hydrogen fluoride on the internal structure of *Pinus ponderosa* needles. *Proceedings of Natural Air Pollution Symposium* 3:164–176

Spotts RA (1969) *Environmental Factors of Pine Tip Burn*. Masters thesis. Colorado State University, Fort Collins

Stolte KW (1982) *Effects of Ozone on Chaparral Species in the South Coast Air Basin*. Masters thesis. University of California at Riverside.

Stolte KW, Bennett JP (1984) *Standardized Procedures for Establishing and Evaluating Pollution Injury on Pines in Permanent Plots*. USDI National Park Service, Air Quality Division, Denver, Colorado

Stolte KW, Miller PR (eds) (1991) *Management Recommendations and Specifications for Plot Design and Sampling Methods to Monitor Long-term Effects of Ozone on Western Coniferous Forests*. Proceedings of a Pine Plot Workshop, March 14–15, 1989, Riverside, California. US Forest Service, Southeastern Forest Experiment Station, Research Triangle Park, NC, 88p

Taylor JK (1985) What is quality assurance? In: Taylor JK, Stanley TW (eds) *Quality Assurance for Environmental Measurements*. ASTM STP No. 867 pp 5–11

Taylor JK (1987) *Quality Assurance of Chemical Measurements*. Lewis Publishers, Inc, Chelsea, MI

Taylor PJ (1977) *Quantitative Methods in Geography*. Houghton Mifflin, Boston

Taylor OC (1974) Air pollution effects influenced by plant-environment interaction. In: WM Duggar (ed) Air Pollution Effects on Plant Growth, A. Chem. Coc. Symp Ser. 3, Washington, DC, pp 1–7

Taylor OC (1980) *Photochemical Oxidant Air Pollution Effects on a Mixed Conifer Forest Ecosystem*. Final report. USEPA, Ecological Research Series, EPA-600/3-80-002

Taylor OC, Miller PR, Page AL, Lund LJ (1986) *Effects of Ozone and Sulfur Dioxide Mixtures on Forest Vegetation of the Southern Sierra Nevada*. Final Report to California Air Resources Board. ARB Contract No. AO-135-33

Thompson MA (1981) Tree rings and air pollution: A case study of *Pinus monophylla* growing in east-central Nevada. *Environmental Pollution, Series A* 26:251–266

Tingey DT, Wilhour RG, Standley C (1976) The effect of chronic ozone exposures on the metabolic content of ponderosa pine seedlings. *Forest Science* 22:234–241

Tingey DT, Wilhour RG, Taylor OC (1979) The measurement of plant response. In: Heck WW, Krupa SV, Linzon SN (eds) *Handbook of Methodology for the Assessment of Air Pollution Effects on Vegetation.* Air Pollution Control Association, Pittsburgh

Treshow M (1970) Ozone damage to plants. *Environmental Pollution* (1):155–161

Treshow M, Anderson FK (1989) *Plant Stress from Air Pollution.* Wiley, New York

Treshow M, Pack MR (1970) Fluoride. In: Jacobson JS, Hill AC (eds) *Recognition of Air Pollution Injury to Vegetation: A Pictorial Atlas.* Air Pollution Control Association, Pittsburgh

Ustin SL, Curtiss B, Martens SN, Vanderbilt VC (1989) Early detection of air pollution injury to coniferous forests using remote sensing. In: Olson RK, Lefohn AS (eds) *Effects of Air Pollution on Western Forests.* Transactions Series, No. 16, Air and Waste Management Association, Pittsburgh, pp 351–378

Van Deusen PC (1987) Testing for stand dynamics effects in red spruce growth trends. *Canadian Journal of Forest Research* 17:1487–1495

Van Deusen PC (1989) A model-based approach to tree ring analysis. *Biometrics* 45:763–779

Van Deusen PC (1990) Evaluating time-dependent tree ring and climate relationships. *Journal of Environmental Quality* 19:481–488

Van Hook C (1974) Fluoride distribution in the Silverbow, Montana, area. *Fluoride* 7:181–199

Visser H, Molenaar J (1986) *Time-dependent Responses of Trees to Weather Variations: An Application of the Kalman Filter.* Report 50385-MOA 86-3041, N.V. KEMA, Arnhem, the Netherlands

Visser H, Molenaar J (1988) Kalman filter analysis in dendroclimatology. *Biometrics* 44:929–940

Vogler DR (1982) *Ozone Injury and Height Growth of Planted Ponderosa Pines on the Sequoia National Forest.* USDA Forest Service, Pacific Southwest Region, Forest Pest Management Report No. 82-18

Walters JW (1978) *A Guide to Forest Diseases of Southwestern Conifers.* USDA Forest Service, Southwestern Region, Forest Insect and Disease Management, R3 78-9

Warren WG (1980) On removing the growth trend from dendrochronological data. *Tree-Ring Bulletin* 40:35–44

Wellburn A (1989) *Air Pollution and Acid Rain: The Biological Impact.* Longman Group UK Limited

Whitby LM, Hutchinson TC (1974) Heavy-metal pollution in the Sudbury mining and smelting region of Canada. II: Soil toxicity tests. *Environmental Conservation* 1:191–200

Williams WT, Williams JA (1986) Effects of oxidant air pollution on needle health and annual-ring width in a ponderosa pine forest. *Environmental Conservation* 13:229–233